GEOTECHNICAL ASSET MANAGEMENT
Implementation Concepts and Strategies

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CTIP

Federal Lands Highway
Commitment to Excellence

Central Federal Lands Highway Division
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FOREWORD

The Federal Lands Highway (FLH) of the Federal Highway Administration (FHWA) promotes development and deployment of applied research and technology applicable to solving transportation related issues on Federal Lands. The FLH provides technology delivery, innovative solutions, recommended best practices, and related information and knowledge sharing to Federal agencies, Tribal governments, and other offices within the FHWA.

The objective of this study was to develop a foundational case for geotechnical asset management as it directly pertains to the unique performance-based needs of FLH partner agencies and to illustrate the attributes and elements of a comprehensive, site-specific geotechnical asset management program and the manner in which it might be implemented as part of on-going transportation asset management efforts within a forest, park, or other federal land management agency. Based on the information collected, this report was produced.

The contributions and cooperation of the WFLHD, CFLHD, and Alaska DOT personnel are gratefully acknowledged.

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Notice

Quality Assurance Statement

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16. Abstract

The purpose of transportation asset management is to meet life-cycle performance goals (safety, mobility, preservation, economics, and environmental aspects) through the management of physical assets in the most cost-effective manner. Geotechnical asset management can be incorporated into the broader practice of transportation asset management. Currently, most agencies manage geotechnical features on the basis of “worst-first” conditions, reacting to failures and incurring significant safety, mobility, environmental, and intangible costs. The goal of geotechnical asset management is to implement project planning and selection on the basis of “most-at-risk” for the asset class with consideration of collective and site specific risks throughout the life cycle. Geotechnical features that can affect the performance of a transportation system include retaining walls, unstable slopes, rockfall sites, embankments, and tunnels. These features can be treated as physical assets of the system and managed like other assets of the system. While not every geotechnical feature exists in agency, those that do can be combined into a single asset class to simplify asset management procedures. Although likely on the high end of expectation, some studies indicate a life-cycle cost savings of up to 60 to 80 percent after the implementation of geotechnical asset management. The geotechnical asset management plan should be based on agency performance goals and integrate risk and life-cycle analysis. It is important to note geotechnical asset management will only be successful when all features that create risk are included. Risk management allows for the probability and consequences of events to be evaluated, which is essential for the integration with agency performance goals. Federal Land Management Agencies can implement geotechnical asset management with a relatively modest investment and using existing resources to assess geotechnical features in a multi-tier, risk-based approach. There is an agency cost associated with inaction on geotechnical asset management.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ADA	American Disabilities Act
AGS	Australian Geomechanics Society
ALARP	as-low-as-reasonably practicable
BIP	Bridge Inspection Program
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
CFLHD	Central Federal Lands Highway Division
EFLHD	Eastern Federal Lands Highway Division
FASB	Financial Accounting Standards Board
FHWA	Federal Highway Administration
FLH	Federal Lands Highway
FLMA	Federal Land Management Agencies
GIP	Traffic Barrier and Guardwall Inventory Program
GIS	geographic information system
NAMS	New Zealand Asset Management Support
NPS	National Park Service
ODOT	Oregon Department of Transportation
PCI	Pavement Condition Index
RIP	Road Inventory Program
SLRA	strategic level risk assessment
TLRA	tactical level risk assessment
TRB	Transportation Research Board
USBR	U.S. Bureau of Reclamation
USFWS	U.S. Fish and Wildlife Service
WIP	Wall Inventory Program
WSDOT	Washington State Department of Transportation
WYDOT	Wyoming Department of Transportation
WYLSO	Wyoming Legislative Service Office

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CHAPTER 1 — INTRODUCTION

The purpose of transportation asset management is to meet life-cycle performance goals through the management of physical assets. Typically, asset management programs have been established for transportation infrastructure elements such as pavements, bridges, and traffic signals and signs. The performance goals of an asset management program can address safety; mobility; preservation; economics; and environmental aspects such as sustainability, pollution prevention, and protection of cultural, historical, and environmental resources. The management objective is to meet performance goals in the most cost-effective manner.

Geotechnical features that can affect the performance of a transportation system include retaining walls, unstable slopes, rockfall sites, cut slopes, embankments, and tunnels. An example of several geotechnical assets is provided in Figure 1. These features can be treated as physical assets of the system and managed like other assets of the system. Further, failures of geotechnical features have resulted in environmental damage, significant repair costs, and even larger economic costs to corridor users and communities. In most cases, the cost of potential risk mitigation options were found to be much less than the economic consequences of the actual failure. Therefore, a purpose and need exists to incorporate geotechnical asset management into the broader practice of transportation asset management.

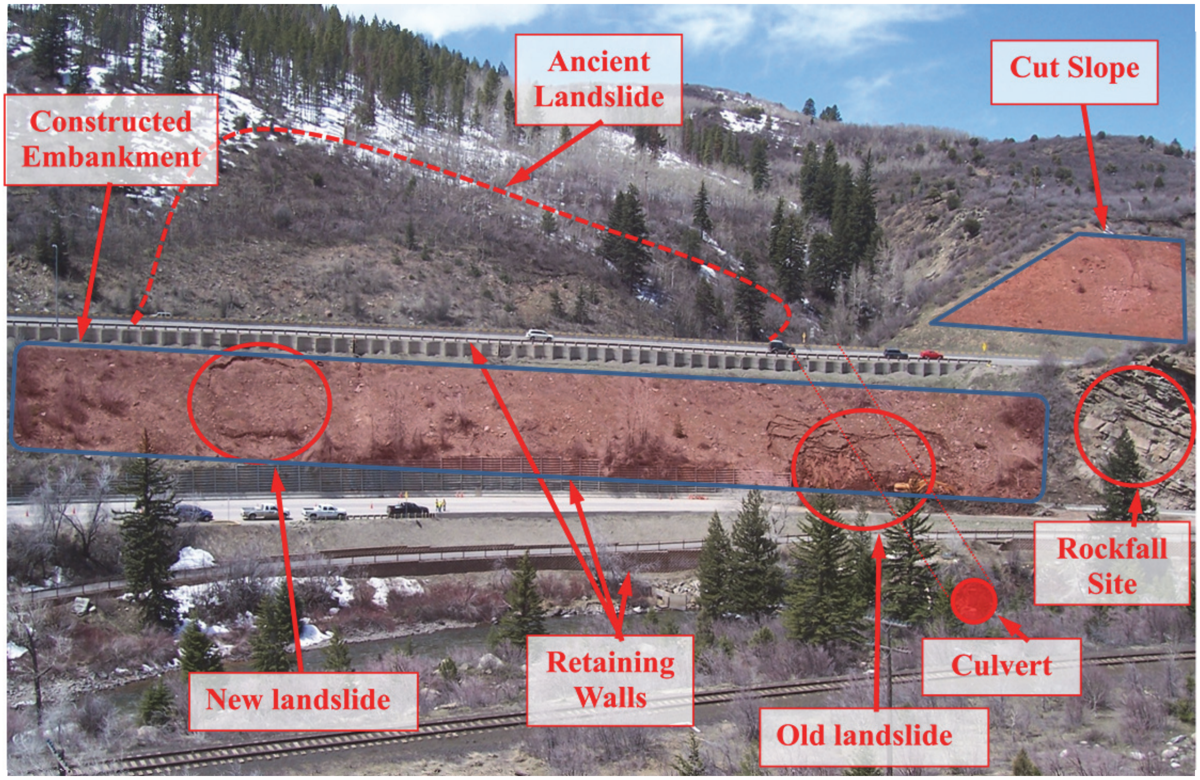

Figure 1. Photo. Example geotechnical assets.

This document presents the general concepts for management of geotechnical features associated with transportation infrastructure. The report also reviews the state-of-the-practice for asset management, value-added aspects of geotechnical asset management, and needed developments to move forward. The focus of the document is on the specialized needs of Federal Land Management Agencies (FLMA), which include environmental impacts, cultural preservation, roadway sustainability, and optimized cost management.

CHAPTER 2 — THE ROLE AND VALUE OF GEOTECHNICAL ASSET MANAGEMENT

Asset management programs are established for various elements of the transportation infrastructure system, including pavements, bridges, and traffic signals and signs. While the definition and methods of application may differ between asset type and agency, the concept of asset management for infrastructure consists of processes that will cost efficiently preserve the physical features that are critical to the performance goals of the agency or owner.

In this regard, the long-term performance and safety of transportation infrastructure throughout the life-cycle depends on the reliability of earth supported components, as well as the reliability of adjacent terrain. Other variables, such as traffic volume and type and maintenance cycles, will affect the long-term performance. Management of each these independent variables (earth conditions, traffic volume, and maintenance) may be required depending on the performance needs and goals of the transportation system owner.

For the purpose of this document, "geotechnical asset management" is defined as a performance based methodology that integrates risk and life-cycle analyses for the geotechnical features that exist in the overall transportation infrastructure. Inherent to this definition are means and methods for feature inventory and condition assessment, and the establishment of agency or owner performance measures. Additionally, geotechnical asset management is a process that can be included into the broader practice of transportation asset management for an infrastructure owner.

The practice or need for management of various geotechnical features has been identified by others (Bernhardt and others, 2003; Perry and others, *cuttings* (2003); Perry and others, *embankments* (2003); United Kingdom Department for Transport, 2003; Kelly and others, 2005; Foltz and McKay, 2008; Stanley and Pierson, 2011; Scott, 2011; and Kidner, 2012). While the term "geotechnical asset management" is not uniformly defined across infrastructure types, the literature presents examples of inventory, assessment, and methods for maintenance decision support and project prioritization based on life-cycle performance expectations.

Geotechnical assets previously identified by others are presented in Table 1. This table provides an introduction to the features that have been previously suggested as geotechnical assets in transportation infrastructure. It is important to note that not all geotechnical features may qualify for consideration in asset management planning. The value and basis for selection of features within a geotechnical asset management strategy is presented later in this report.

Table 1. Geotechnical asset types identified by others.

Geotechnical Asset Type	Reference
Embankments and Slopes (to include rock slopes, cut slopes, landslides, and rockfall sites)	Bernhardt and others (2003) Perry and others, *cuttings* (2003) Perry and others, *embankments* (2003) Kelly (2005) Stanley and Pierson (2011) American Association of Highway and Transportation Officials (AASHTO) (2011a)
Tunnels	Bernhardt and others (2003) AASHTO (2011a)
Earth Retaining Structures (retaining walls, reinforced soil slopes, and earth and rock buttresses)	Bernhardt and others (2003) Brutus and Tauber (2009) DeMarco and others (2010) Stanley and Pierson (2011)
Culverts or Drainage Channels	Bernhardt and others (2003) DeMarco and others (2010) AASHTO (2011a)
Foundations	Bernhardt and others (2003) Stanley and Pierson (2011)
Pavement Subgrade	Bernhardt and others (2003)
Subgrade and Land within Right-of-Way	United Kingdom Department for Transport (2003)
Buried Reinforcing Elements, Rock Bolts, Tieback Anchors, and other Buried Structural Elements	Stanley and Pierson (2011)
Material and Quarry Sites	Stanley and Pierson (2011)
Horizontal Drains	Stanley and Pierson (2011)

TRANSPORTATION ASSET MANAGEMENT OVERVIEW

Transportation asset management is a strategic and systematic process of identifying, operating, maintaining, upgrading, and expanding physical assets effectively throughout their life-cycle. It focuses on business and engineering practices for resource allocation and usage, with the objective of better decision-making based upon quality information and well-defined objectives (AASHTO, 2011b). Per the International Infrastructure Management Manual (New Zealand Asset Management Support [NAMS], 2006), the purpose of transportation asset management is to meet a required level of service, in the most cost-effective manner, through the management of assets for present and future customers.

Transportation asset management has been well documented in the United States since 1999 when the Office of Asset Management was established by the Federal Highway Administration (FHWA). As of the time of this report in 2012, the FHWA maintains an Office of Asset Management, Pavement, and Construction and an Office of Transportation Performance Management, which are both under the FHWA Office of Infrastructure.

The frequently referenced and established assets common amongst transportation asset management publications include pavement and bridge management, maintenance management, and transit management. AASHTO (2011a) emphasizes that transportation asset management should be a continuous improvement process with gap analysis to guide the improvement. Other assets referenced in various transportation asset management resources include intelligent transport systems facilities, culverts, signs, traffic barriers, sound barriers, tunnels, stormwater control features, maintenance and communication buildings, bike and pedestrian facilities, slopes and rockfall sites, rest areas, utilities, traffic signals and lighting, American Disabilities Act (ADA) compliance access, and pavement markings.

The implementation of transportation asset management is a process that addresses questions about:

- The current state of assets,
- The required level of service and performance delivery,
- Identification of the assets that are critical to performance,
- The investment strategies for operation, maintenance, replacement, and improvement, and
- Long-term funding strategies (AASHTO, 2011a).

Per AASHTO (2011a), the early stages of asset management are characterized by simple analysis and documentation of existing practices. As the practice evolves, agencies develop inventories, assess condition and performance, perform risk assessments, analyze benefits and costs, and implement planning and management strategies. A characteristic of advanced transportation asset management should include "…long-term, life-cycle management plans for each asset group and for some individual assets. These plans show the projected outcomes of policies and programs in terms of cost, performance, and risk (AASHTO, 2011a)."

GEOTECHNICAL FEATURES SUBJECT TO GEOTECHNICAL ASSET MANAGEMENT

Asset Identification

A key process in transportation asset management presented in AASHTO (2011a) is the identification of assets that are critical to performance. Thus, it is important to understand the concept of assets in the context of an infrastructure system. The term "asset" informally suggests a useful or valuable component that is owned. A formal definition of "asset" is the probable future economic benefits that are controlled by a particular entity as a result of past transactions or events (Financial Accounting Standards Board [FASB], 2008).

Additionally, assets can consist of tangible assets that represent a physical presence with a measurable value and also intangible assets that lack a material presence and, therefore, may be more difficult to quantify. The individual physical elements of a transportation system, such as pavements, bridges, or tunnels, which directly contribute to the value of the system through mobility, are tangible assets. The tangible asset value also can be based on the replacement cost for a particular feature and the salvage value of the surplus materials. An example of a geotechnical tangible asset value is presented in the Retaining Wall Inventory and Assessment Program for the National Park Service (NPS), which identified wall assets for a portion of the NPS system with a total estimated value of over $400M (DeMarco and others, 2010). In contrast, the economic benefit to a community or region that results from the mobility of freight and passengers throughout the life cycle is an example of an intangible asset. Another intangible asset of an infrastructure system is user safety, which contributes to the overall value of the system, but is not readily quantified.

An owner may consider the geotechnical features of a transportation system (e.g., retaining walls, rockfall protection) a liability because of the maintenance burden or financial expense associated with repair and rehabilitation or the difficulty in quantifying value. Additionally, unplanned failures of geotechnical features often create a strained cost and performance liability for an owner or management agency. However, these physical features have tangible and intangible values that are critical to the performance of transportation infrastructure throughout the life cycle and should be managed as an asset class. The funding obligations required to construct, maintain, and repair tangible assets are the liabilities, as well as the cost of evaluating and asset management planning.

Examples of the Value of Geotechnical Assets

While the classification of geotechnical features as either an asset or liability could be subject to further discussion, the value these features provide in the context of infrastructure performance is measurable. This is demonstrated by reviewing the failures of geotechnical features that resulted in financial loss, environmental and historical property damage, compromised public safety, reduced mobility, or required reconstruction. Examples of the significant impacts to corridor performance from the failure of geotechnical features are briefly illustrated by the following case histories.

An important consideration that is evident from these examples is the potential for much larger relative failure or mitigation costs when compared to road user costs associated with pavement or other asset types. For example, user costs for repair of a failed pavement section may be lower than the cost of stabilizing or reconstructing failed retaining wall because detours can typically be confined within the project limits or existing roadway. Many geotechnical failures will have increased user or community impacts that are associated with lengthy detours, prolonged closures, or private property damage. Further, the cost associated with management of geotechnical hazards prior to failure can be offset by the potential for savings when compared to these failure costs.

Ferguson Slide, California

The Ferguson rock slide in April 2006 closed the most accessible and direct route for tourists visiting Yosemite National Park, as well as local residents (Caltrans, 2007). Because of the economic consequences from the closure, a state of emergency was declared by Mariposa

County. During the 92-day closure period, the estimated business losses were $4.8 million (Harp and others, 2008). A single lane detour was opened by August 2006; however, the detour could not accommodate large vehicles and the event continued to have a negative economic impact to several local communities, businesses, and Yosemite National Park. Post event analyses provide specific examples of community impacts, which included business closures, a 30 percent reduction in lodging revenue, and up to a 60 percent decrease in other business activities (Caltrans, 2007). In 2008, an $8 million project was completed to construct detour bridges that allow for larger vehicles through the corridor. A project to permanently restore full access is currently in the planning phase with construction cost alternatives ranging from $18 to $378 million (Caltrans, 2012).

Tennessee and North Carolina Rockslides

In 2009, two separate rockslide events on I-40 in North Carolina and US-64 in Tennessee resulted in nearly six months of road closures. A study on the effects of these events indicated several local and regional impacts that include greater than 50 percent revenue decreases for lodging operators, 30 to 90 percent reduction in restaurant and retail business, 25 percent decrease in gasoline sales, and $200,000 in lost revenue for a hospital (HDR, 2010). The slides also had a combined total transportation cost of $197M, which resulted from costs associated with increased vehicle operation, detour travel time, emissions, congestion, and pavement maintenance on alternative routes. These costs were based on an additional 133 million miles of travel that were required because of the closures. Further, while truck traffic was approximately 28 percent of the corridor volume, it represented almost one-half of the estimated economic value. There also are environmental impacts that are not quantified but likely significant when considering traffic noise and water quality.

Vail Pass Culvert Failure

Figure 2. Photo. Vail Pass culvert failure.

In 2003, a substantial rain event, coinciding with the spring runoff, occurred in the area of Vail, Colorado. During the event, a depression, shown in Figure 2, was reported in the westbound lanes of I-70 at approximately 1:00 a.m. on June 1. The depression expanded over a 12-hour period until a catastrophic roadway collapse occurred and closed the highway (Liu, 2003). The failure was the result of soil piping from water leakage in a 66-inch-diameter culvert. The culvert was in an engineered embankment at a maximum depth of 40 feet below the interstate and carried Bighorn Creek toward the confluence with Gore Creek, which flows through the Vail Golf Course and Vail Village, a top tourist attraction in Colorado. After the failure, both directions of I-70 were closed for approximately three days until the embankment could be stabilized to create a single-lane detour for each direction. The detour was expanded to two lanes (original width) in both directions 16 days after the failure. I-70 was opened in the original configuration 22 days after the event. During the event, Bighorn Creek flowed in a relatively uncontrolled fashion through the residential streets of East Vail and was contaminated with sediment. The total repair cost for I-70 and Town of Vail infrastructure was $4.2M, and the transportation user costs were estimated to be over $4M. As an outcome of this event, the Colorado Department of Transportation (CDOT) incurred a cost of $2.1M for the statewide inspection of 6,273 culverts and identified 205 critical structures that will require an estimated $56M for repair or replacement (Mommandi, 2011).

Beartooth Pass Closure

The Beartooth Highway is an important transportation route between Red Lodge, Montana, and Yellowstone National Park, providing major economic benefits to adjacent communities in Wyoming and Montana. Additionally, the Beartooth Highway is the only access to the Northeast Entrance of Yellowstone National Park (Atkins, 2011). During seasonal snow clearing operations in May 2005, the runoff from a rain-on-snow precipitation event was concentrated on the roadway until the stormwater could not be contained. The resulting runoff triggered debris flows that moved over 100,000 cubic yards of soil and rock down the steep slopes and damaged the roadway in 13 locations over a 10-mile stretch (Perkins, 2006). Figure 3 shows the roadway and environmental damage associated with one of the debris flow sites. After the May event, the highway was closed until October 15, 2005, to complete a $19M reconstruction project during which time access to Yellowstone National Park was greatly restricted. A subsequent planning study for prior-planned construction projects along the Beartooth route indicated approximately 13 percent of all earnings in Carbon County, Wyoming, were associated with tourism along the corridor (Atkins, 2011). Therefore, closure of the Beartooth Highway resulted in significant earning impacts for the local communities, as well as revenue to Yellowstone National Park.

Figure 3. Photo. Debris flow damage on Beartooth Pass.

To prevent a repeat of the runoff concentration that triggered the debris flows, dual runoff drainage/debris handling systems were designed and constructed during the repair project.

However, the oversteepened sides of the debris chutes themselves pose a debris flow hazard even without the runoff concentration. Probabilistic and deterministic debris flow hazard models were developed, and analyses were performed to determine the likely volumes and recurrence of future debris flows from the eroded chutes. Based on the volume and recurrence estimates, a hazard reduction matrix was developed to assist the Montana Department of Transportation in selecting debris flow hazard mitigation measures. The measures selected for design and construction included three debris flow fences, one rockfall drape, and two debris flow training berms (Perkins, 2006). The cost of these preventive measures was relatively minor when compared to the highway repair budget.

Environmental Damage and Considerations

While it is not well documented in the literature, the failure of geotechnical features in a transportation corridor can result in environmental damages. This can include damages to native vegetation, uncontrolled stormwater flow, sediment releases into waterways, disruption of wildlife habitat, noise impacts from congested or redirected traffic, release of harmful elements (e.g., salt-bearing soils, naturally occurring asbestos, mine tailings), and aesthetics or cultural loss. Additionally, the unplanned reconstruction of roads or other facilities is not a sustainable process. It can result in excess pollution from construction equipment, longer detour routes, and unscheduled consumption of resources.

Additionally, the performance of geotechnical features and other transportation assets can be influenced by rapid changes in the surrounding environmental conditions or terrain. For example, recently burned areas have an increased vulnerability to debris flows that generate larger scour and depositional features (Santi and others, 2008). Figure 4 shows a post-fire debris flow that plugged a small-diameter drainage culvert, which resulted in an impoundment against the highway embankment and deposition of fine-grained sediment into forest lands. While the environmental damage during a forest fire cannot be managed, the potential risks to geotechnical and other transportation assets and can be evaluated, quantified, and managed to varying degrees. As discussed in Cannon and DeGraff (2008), reducing the risk from an increase in post-fire debris flows requires effort to reduce the vulnerability of people and property. After a wildfire, the constraints associated with time, cost, and physical conditions may prevent mitigating measures at all possible locations. Only by focusing available resources on the critical locations can effective risk reduction be achieved. By using asset management and establishing performance goals, it may be possible to

Figure 4. Photo. Post-fire debris flow impounded against a highway embankment.

achieve risk reduction before the environmental event.

Life-Cycle Performance Considerations

Per AASHTO (2011a), the intent of asset management programs is the development of long-term, life-cycle management plans, which ultimately are measured against cost, risk, and performance goals.

For geotechnical features within a transportation system, the failure modes are often related to or resemble a natural hazard event and significant repair costs may be incurred. However, a distinction must be made between emergencies that result from natural hazards versus emergencies that result from neglect, such as the Vail Pass Culvert example. As demonstrated in the examples presented above, the transportation agency can be forced to respond in an unplanned, reactionary manner. This is often termed "worst first" hazard management and does not follow an asset management framework. This approach requires an owner or agency to have a means for managing and funding emergency projects and also may require a greater commitment of funds over the life cycle. ***For emergencies that result from neglect of assets, asset management is the means to reduce the financial, operational, and safety risks that occur throughout the life cycle***.

As shown in the Ferguson Slide example, the temporary mitigation costs were over $8M, economic impacts are near $5M, and the permanent mitigation project will be a minimum of $18M. In this case, there likely were measures that could have been implemented for significantly less than the required minimum of $31M that may be expended to mitigate the hazard after complete failure. This value does not include the several million dollars of economic impacts. The goal of an asset management program in these situations would be to perform project planning and maintenance activities in a manner that minimizes the financial liability throughout the life-cycle while obtaining desired performance.

Asset management has been applied to roadway and railway embankments and permanent cut slopes for more than a decade in the United Kingdom. As summarized in Perry and others, *cuttings* (2003) and Perry and others, *embankments* (2003), studies on the benefit of proactive maintenance and renewal strategies (i.e., geotechnical asset management) for railroad and motorway embankments in the United Kingdom indicate life-cycle cost savings of approximately 60 to 80 percent per unit length of embankment. In these situations, the *need for emergency stabilization projects is significantly reduced and owners can benefit from more efficient use of resources and long-term cost savings*.

The performance risk to a transportation facility from the failure of geotechnical assets generally will increase with time as the individual features progress through their life cycle. This is similar to the concept demonstrated by asset deterioration curves that exist for other asset types, such as roadway pavements. Figure 5 presents an example deterioration curve for pavement, which also illustrates the effect of preservation actions. As shown in the figure, the rate of deterioration is initially slow and less than one-half of the condition loss occurs in the first 15 years. However, the same condition loss is observed in approximately one-half the time as the deterioration rate increases. Based on the rate of deterioration, there is a financial advantage to maintaining the asset in the upper quarter of condition where maintenance costs are generally lower. While Figure 5 is based on pavement condition data, the general trend for the deterioration of geotechnical features is anticipated to be similar.

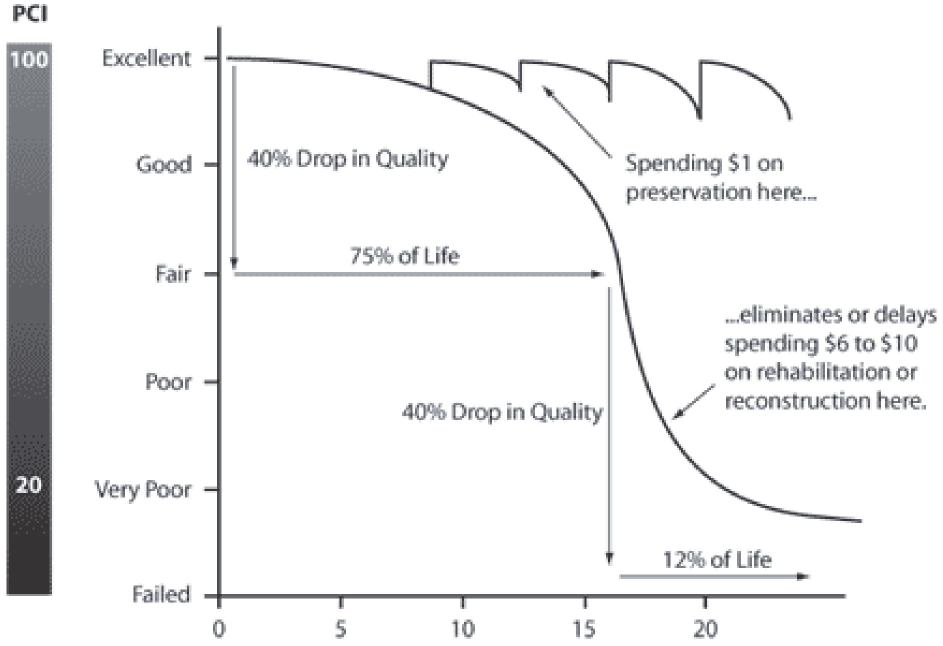

Figure 5. Plot. Pavement deterioration curve with preservation options.
(PCI = Pavement Condition Index) (Galehouse and others, 2006)

There are a wide range of failure scenarios and deterioration criteria that can be considered throughout the life cycle of geotechnical features in an asset management plan. As indicated in the United Kingdom example, asset management can be used to avoid catastrophic failures as well as direct agency efforts toward reducing the long-term operational and financial impacts from anticipated failure modes. Geotechnical asset management should be the process that allocates funds towards maintaining features at an acceptable performance level. Further, the life cycle or service life of geotechnical features may not be a reliable parameter without measuring factors related to safety, operational performance, and cost, which are indicative of the end of an asset life cycle. As presented by Stanley and Pierson (2011), levels of service and performance measures for unstable slopes have been established based on criteria that satisfy the policies and goals of the Alaska Department of Transportation and Public Facilities.

Furthermore, it is critical that an owner does not overlook the need for geotechnical asset management at the start of the life cycle, which includes planning and construction details that consider optimizing the life cycle and performance metrics. By addressing geotechnical asset management at the start of a project life cycle, an owner can recognize efficiencies later in the life cycle. As an example, common rockfall barrier systems are shown in Figure 3. The performance life of these fence systems is dependent on the inspection and replacement of critical components, such as anchor cables and associated connections, as well as removal of accumulated rockfall. For the photograph on the left, the critical fence components will be more difficult to inspect and costly to replace because there is not space available for equipment or worker access. Furthermore, accumulated rockfall removal will likely require temporary reductions in operational performance because lane closures are needed for equipment and personnel. Conversely, the fence system on the right of Figure 6 illustrates an example where the maintenance, cleaning, and inspection will be a more efficient process with minimal impact to operational or mobility performance indicators, ensuring a longer life cycle.

Figure 6. Photos. Example rockfall fence installations.

Historically, owners have overlooked the need for asset management in the initial portion of the life cycle. This is because the asset is in good condition and a deterioration curve would suggest a low rate of condition loss regardless of transportation or geotechnical asset management strategy. Furthermore, the low frequency of failure shortly after construction may allow contingency funds and resources to be directed towards immediately beneficial efforts, such as other new construction. The challenge for the owner will be as the deterioration cycle progresses, the difference in system performance will be more dependent on asset management strategies. As shown in the deterioration curve example, each year of a life cycle without a rational management strategy will result in asset class deterioration and present an increased financial burden to the owner and users. While this condition can cause an immediate financial, safety, or other liability, it is important for agencies and owners to recognize the liability is the result of asset deterioration and can be corrected.

Geotechnical Features and Asset Management

Proposed features that could be incorporated into a geotechnical asset management program are presented in Table 2. These potential geotechnical features were selected from examples in the literature as presented in Table 1. The selections also were based on the feature having a measurable tangible asset value and a contribution to the performance (intangible benefit) of a transportation system. Examples of tangible assets and intangible benefits are shown in the table along with examples of feature-specific liabilities. In general, all of the geotechnical features would be susceptible to natural degradation and the associated liabilities would increase over time. Furthermore, deferred maintenance or neglect can reduce the service life of these features, often resulting in catastrophic failure in addition to the failure that occurs during natural emergency situations (e.g., floods, fires, major precipitation events, earthquakes).

The identification of geotechnical features as an asset often will depend on the agency experience or geographic considerations. For instance, tunnels may not be uniformly identified as a geotechnical asset because of the limited existence of these structures within various transportation systems or corridors. For example, there are approximately 70 tunnels within the National Park system, but the distribution of these tunnels is variable between parks and the value each tunnel contributes to the system is variable. Depending on the performance goals for an owner or agency, the geotechnical features presented in Table 2 could be separated or selected as individual assets or grouped into a single geotechnical asset class that is evaluated for a transportation system or corridor. Additional discussion on this topic is presented later.

The features presented in Table 2 are not meant to be a complete list. Rather, it is a guide for identifying/selecting assets that may influence the performance measures for a transportation agency or corridor.

INCORPORATION OF GEOTECHNICAL FEATURES INTO FLMA TRANSPORTATION ASSET MANAGEMENT PLANS

Other transportation infrastructure assets such as pavements, bridges, signs, and intelligent transportation systems are supported by or are in close proximity to various geotechnical features. The transportation infrastructure also is bounded by private property or public lands with recreational, commerce, or cultural values. Additionally, utility networks (fiber optics, electrical services, water transmission) may be located within or adjacent to transportation corridors. The failure of a geotechnical feature within a corridor may damage the other transportation assets or private property, which leads to unplanned maintenance and financial loss for all stakeholders. Therefore, a goal of geotechnical asset management is to develop a strategy that reduces the financial and maintenance cost associated with geotechnical features to less than the life cycle cost that occurs due to unplanned repair or reconstruction activities.

Table 2. Possible geotechnical features for asset management.

Geotechnical Feature	Tangible Asset Components	Contribution Towards Intangible Value	Associated Liabilities
Tunnel	▪ Substructure elements (structural lining, ground reinforcement) ▪ Electrical and mechanical systems	▪ Typically shortens travel time ▪ Provides a safer route through hazard avoidance ▪ Reduces land disturbance and property acquisition	▪ Maintenance ▪ Staff for facility operation (fire protection, systems control)
Earth Retaining Structures and Retaining Walls	▪ Concrete or modular facing systems ▪ Earth reinforcement ▪ Engineered fill	▪ Reduces land disturbance and property acquisition ▪ Straightens and widens roadway ▪ Reduced travel time through shorter alignment	▪ Repair of components damaged by road users (accidents) or experiencing natural degradation
Embankments	▪ Imported fill materials ▪ The structural section supporting pavement	▪ Allows for increased speeds by reducing vertical alignment change ▪ Support road surface and increase longevity of surfacing materials.	▪ Erosion ▪ Maintenance of vegetation ▪ Slope/subgrade instability
Road and Rail Subgrade (includes ground improvement)	▪ Import fill materials such as gravel or ballast ▪ Controlled fill soils	▪ Supports the pavement or rail structure	▪ Water infiltration ▪ Soils with expansion or collapse properties
Modified Native Slopes (cuts)	▪ Re-vegetation ▪ Erosion control	▪ Reduces land disturbance and property acquisition	▪ Erosion ▪ Maintenance of vegetation ▪ Aesthetics
Slopes (well performing slopes; rockfall; rockslides and landslides; could also include avalanches)	▪ Stabilization elements such as ground anchors or rock dowels ▪ Protection measures such as barrier, mesh, diversion and retention structures ▪ Instrumentation	▪ Protects property and human life ▪ Reduces land disturbance and property acquisition	▪ Unfavorable drainage ▪ Repair of unstable slopes and roadway features ▪ Risk of life loss from rockfall, debris flow, and avalanche features
Culverts	▪ Pipe ▪ Inlet and outlet protection ▪ Embankment soils ▪ Wall fills and reinforcements	▪ Facilitates roadway drainage ▪ Typically the lowest cost option for passage of surface water through roadway easement or right-of way	▪ Corrosion of steel pipes ▪ Abrasion of concrete pipes ▪ Alignment issues due to foundation movement ▪ Soil loss or sinkholes from uncontrolled water flow ▪ Blocked inlets
Quarry and Material Sites	▪ Owner supplied materials	▪ Readily available supply of materials for earthwork construction	▪ Environmental reclamation ▪ Maintenance and inspection during periods of non use.

Incorporation of geotechnical asset management is valuable for agencies where these assets present a measurable risk to level of service and system performance. Based on discussions with geotechnical staff from Federal Lands Highway (FLH) and state departments of transportation, there is an awareness of principles of geotechnical asset management and the benefit of proactively addressing geotechnical features that impact agency performance measures. There are also several examples of inventory and management programs for individual geotechnical features, such as rockfall sites and earth retention structures. However, the deployment of a formally defined, comprehensive geotechnical asset management program has been limited.

General Strategies for Geotechnical Asset Management

Based on a review of existing and emerging practices, there are two suggested approaches for the management of geotechnical assets: (1) management of a specific feature such as rockfall sites or retaining walls, or (2) management of a group of features into a single geotechnical asset class. When selecting a strategy, ***it is important for an agency or owner to establish the performance criteria of the asset management program, as well as the available resources to implement and maintain the program***.

For several state departments of transportation, the initial practice of geotechnical asset management began with implementation of rockfall hazard systems, which provide a means for ranking hazard sites and prioritization of mitigation efforts. The Oregon Department of Transportation (ODOT) began development of the first rockfall hazard rating system in 1984, with full implementation by 1990 (Pierson and others, 1990). As of 2012, there are 25 public transportation agencies that use a rockfall hazard rating system (Transportation Research Board [TRB], 2012). In Washington and Oregon, the state transportation department programs have expanded to include rockslide and landslide features in a broader unstable slope category (ODOT, 2010; Washington State Department of Transportation [WSDOT], 2010). The Alaska Department of Transportation and Public Facilities is also currently developing a similar program.

The initiation of the rockfall management programs has occurred in regions where rockfall has caused fatalities or other high profile events and there is agency support for proactive strategies for hazard reduction. With the exception of ODOT, there are limited cases where an agency has formally initiated management of other geotechnical features, such as retaining walls or tunnels. The reasons for limited management of geotechnical features beyond rockfall programs may include insufficient staff resources, lack of specified performance criteria, or absence of standardized transportation and geotechnical asset management practices. While management of geotechnical features is limited, the section *"Examples of the Value of Geotechnical Assets"* (page 6), provides several examples of financial impacts. Additional research is in progress that demonstrates the purpose and need for geotechnical asset management.

The current structure of rockfall hazard programs generally requires an initial investment of staff resources to develop the agency specific rating criteria, perform site inventories and preliminary assessments, and summarize the results into a management plan. In the case of separate management programs for each geotechnical feature, a similar or larger effort would be required for elements such as retaining walls or culvert crossings. Depending on the areal distribution of these geotechnical features, the inventory process could require several years unless a large-scale staff and/or consultant mobilization is devoted to the task.

For management of rockfall sites, there is a relatively well-established process that has been implemented by several state departments of transportation as well as major freight railroads. Therefore, agencies are able to draw from an existing knowledge base when managing rockfall hazards. While there are isolated examples of management programs for other geotechnical features, such as retaining walls or landslides, there is not a similar level of standard practices that could easily be adapted by other agencies. The deficiency in standardized practices does not suggest that agencies and owners have determined geotechnical asset management to be without financial merit. Rather, transportation asset management practices are developing and cost management for transportation assets is anticipated to increase in the future; hence, the purpose for this document.

In situations where agency resources are limited and management of multiple features is required based on transportation performance measures, a strategy that incorporates multiple geotechnical features into a single asset class may be warranted. To our knowledge, this approach is not currently used within transportation agencies in the United States; however*, **there are examples of applied performance management for a grouping of several geotechnical features in other countries and different infrastructure systems.*** These examples are discussed in further detail below.

India Railway and Highway Corridor

A quantitative, risk-based analysis was used to develop a mitigation and management strategy for 901 landslide, rockfall, and debris flow features within a transportation corridor in southern India (Jaiswal and others, 2010). The corridor consisted of 10.5 miles of highway and 15 miles of railway. The analysis evaluated the direct financial risks to the alignment, vehicles, and the potential for economic disruption, as well as the risk to life. While the analysis did not consider all geotechnical features within the corridor, the approach did group several slope failure types into a single class of features and asset management principals were applied for the purpose of long-term project planning and risk reduction. This is in contrast to many current programs in the United States where the hazard management strategy separates the geotechnical slope features into individual programs, such as only rockfall sites.

Landslide Risk Management Concepts in Australia

A quantitative approach for assessing the risk from slope hazards, such as landslides and rockfall, was developed by the Australian Geomechanics Society (AGS, 2000). The assessment considers both financial and life risks. While this numerical approach is directed at individual sites, the results are incorporated into a management process that considers tolerable risk criteria (i.e., performance measures) and establishes a treatment plan. Furthermore, the AGS guidelines indicate care should be taken when assessing risk from individual sites and suggests risk management should consider the sum of risk from all landslides between destination points rather than a single slope (AGS, 2000). This approach would be consistent with a corridor geotechnical asset management strategy.

The AGS guidelines present quantitative methods that may be applicable for the risk assessment phase of a geotechnical asset management plan. Of note, AGS (2000) indicates that the contribution to total corridor risk is often greater for smaller, more frequent events rather than for large, rare events. This conclusion may differ from the outcomes that may result from a rockfall hazard plan. Therefore, the differentiation between hazard and risk should be considered during the development of geotechnical asset management plans.

United Kingdom Embankment and Cut Slopes

Geotechnical asset management is an established practice for major earthworks associated with railway, road, and canal infrastructure in the United Kingdom. The geotechnical features included in this asset management strategy includes fill structures such as embankments subject to settlement, sliding or foundation failure, and cut slopes subject to landslides, rockslides and rockfall (Perry and others, *cuttings*, 2003 and Perry and others, *embankments*, 2003). The geotechnical assets are managed on the basis of a specific route or network of routes, which would be similar to a transportation corridor in the United States.

The established practices in support of a geotechnical asset management program, as presented in Perry and others, *cuttings (*2003) and Perry and others, *embankments (*2003), include a "strategic level risk assessment" (SLRA) and a "tactical level risk assessment" (TLRA). For the strategic assessment, all features (slopes or earthwork fills) are identified to qualitatively categorize the level of risk in a probability and consequence matrix. The product of probability and consequence is the risk. To avoid subjective bias, the SLRA uses a structured approach that assigns qualitative grades such as low, medium, and high to produce a risk profile for the corridor or route. An ***essential aspect of this process is the establishment of generalized objectives (performance goals)*** by which the strategic assessment is completed. Furthermore, strategic assessment is a continuous process that can evaluate the change in geotechnical features throughout the corridor life cycle.

The tactical assessment is performed on sites identified in the strategic risk matrix that produce the greatest relative risk. The TLRA also considers probability and consequence; however, the process is more thorough and uses quantitative methods. The outcome of a tactical assessment will be the selection of a mitigation option with the greatest cost-benefit ratio that also reduces risk to an acceptable level (Perry and others, *cuttings*, 2003). Additionally, the asset management program includes a regular process of SLRA on the order of every five years.

Landslide Risk Management for Saskatchewan Highway Network

In 2003, Saskatchewan Highways and Transportation implemented a risk-based system for prioritizing and managing geotechnical and landslide hazards within the transportation network. The selected method for management incorporates a risk-based approach that considers probability and consequence factors (Kelly and others, 2005). The process includes a field inspection to collect information on location, general observations, and a brief description of distress. The consequences are defined based on qualitative impacts to safety, maintenance, and mobility. A panel of experts was selected to determine the probability and consequence factors for 69 sites identified in a rapid assessment phase and a relative ranking was created. The values are used by the agency to determine the priority for future monitoring and investigation projects.

Dam Safety

The U.S. Bureau of Reclamation (USBR) manages an inventory of 370 dams and dikes using a comprehensive risk assessment to support decisions and project prioritization for dam safety (Scott, 2011). Of note, this process was needed because of the limited resources available within the USBR and has been applied since the mid-1990s. As part of the USBR dam safety management program, the potential failure modes for each dam are identified. While a dam obviously differs from transportation infrastructure, there are common geotechnical features that can cause failure, such as embankment damage, seepage or landslides. For comparison to asset management practices in transportation infrastructure, a dam could be considered equivalent to a corridor which has both a tangible and intangible asset value.

With regards to inventory of failure modes, Scott (2011) indicates this is a critical initial process that must be thorough otherwise the results of any future analysis will have low value or may be incorrect. If a failure mode is not identified, the assessment and risk screening for the entire dam will be incomplete. This conclusion is important to consider when developing an asset management strategy that is based on performance measures for various geotechnical features.

Similar to the geotechnical asset management practice for transportation earthworks in the United Kingdom, the USBR procedures develop a qualitative or semi-quantitative risk matrix that screens failure modes on the basis of relative contribution to risk (probability and consequence). Subsequent analysis consists of a detailed quantitative process that is directed towards features that present the greatest risk. The purpose of this two phased approach is to concentrate resources on the most critical failure modes because of the substantial effort that is required for quantitative analysis (Scott, 2011). During the quantitative analysis, the risk for each critical failure mode can be summed into a single risk value that can be compared to the values for other dams in support of a broader management strategy.

The USBR management strategy is directed at allocating several hundred million dollars of expenditures to meet Dam Safety Program performance goals related to life safety (number of fatalities) and failure probability of dams. Further, the final prioritization of projects considers the risk values in conjunction with other factors such as reliability of data, the sensitivity of failure modes to low probability climatic or geologic events, the relationship between risk reduction and mitigation costs. These steps in project prioritization prevent USBR from addressing risk reduction solely on a worst first basis.

Green River Levees Rapid Assessment

Levees are linear facilities that traverse different terrain and geologic environment, provide a means for control of water, and can have significant regional economic effects if failure occurs. Levees are constructed embankments that can fail due to poor foundation conditions, slope instability, settlement, and seepage. These are similar characteristics to a highway corridor.

To guide the decision process for allocation of limited resources to levee maintenance and repair, King County, Washington, used reliability and risk assessment to evaluate the modes and consequences of levee failure. Rapid assessment was used to quickly develop a broad overview of conditions before more intensive, site-specific reliability and risk assessments were undertaken (Ellis and others, 2008). The cost-effective approach was designed to be completed quickly by relatively inexperienced, but well-trained, personnel. The results of the rapid assessment as shown in Figure 7 were used to focus more intensive quantitative reliability analyses on the levee segments with the highest risk score as a basis for repair and maintenance decisions for the life cycle.

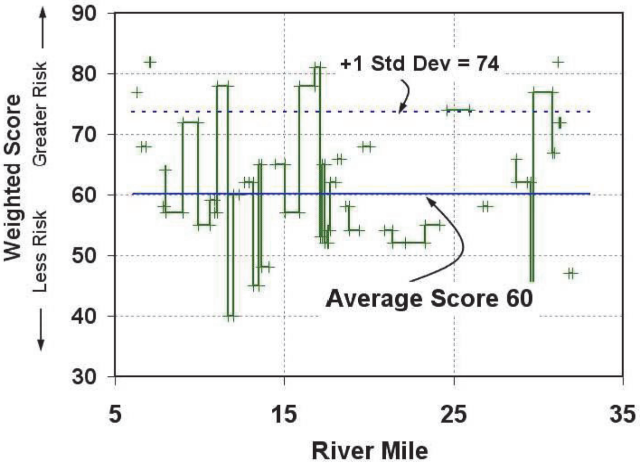

Figure 7. Graph. Example levee risk ranking.

Geotechnical Asset Management Needs and Challenges for Federal Land Management Agencies

As indicated in the section *"Examples of the Value of Geotechnical Assets"* (page 6), there are several examples of geotechnical failures that can be used to demonstrate the value these features contribute towards the corridor performance. To further evaluate the potential for geotechnical asset management to improve FLMA corridor/roadway performance, discussions were held with Central Federal Lands Highway Division (CFLHD) planning and program management staff. The purpose of the meetings was to understand the role of geotechnical features in project programming and planning and the limitations to implementing asset management for the various FLMAs.

All staff indicated a need to be more efficient with the available funds and recognized the potential for geotechnical asset management to add value into the planning process. There also is an opinion that geotechnical asset management must show *measurable* value-added benefits to be involved in the planning process. The conclusions from these discussions can be summarized as follows:

Data Availability and Management

In many cases, the condition and inventory data exist within FLH; however, these data may be dispersed between internal and external stakeholders or not centrally managed. Additionally, the data may be maintained in individual and different database formats and the information in one data set is not compatible or linked to another. These data can include the Road Inventory Program (RIP), Bridge Inspection Program (BIP), Wall Inventory Program (WIP), and Traffic Barrier and Guardwall Inventory Program (GIP), as well as individual agency databases that may track construction history, maintenance, and accident history.

A challenge for implementation of geotechnical asset management for the FLMAs will be the location and accessibility of data for planning and engineering staff. For example, the RIP data for NPS roads are generally dispersed through the different FLH divisions (though centrally managed through Eastern Federal Lands Highway Division [EFLHD]), while all RIP data for U.S. Fish and Wildlife Service (USFWS) are maintained by CFLHD. Based on discussions with CFLHD staff, there are data management improvements presently occurring within FLH, such as cloud storage of data and user accessibility that will facilitate the implementation of geotechnical asset management. Additionally, the data management challenges are not unique to FLH or the FLMAs, and there are several examples of other public agency process improvement efforts to address this issue (Perry and others, *cuttings*, 2003; Perry and others, *embankments*, 2003; Wyoming Legislative Service Office [WYLSO], 2008; Totman, 2010).

The discussions with CFLHD staff indicated improvements to data availability, access management, and standardization of data formats are ongoing. Therefore, the constraints imposed by data collection and management are continually decreasing and this is not anticipated to be a barrier to implementation of geotechnical asset management.

Differences in Asset Management Needs for Federal Land Management Agencies (FLMA)

In general, transportation asset management practices are implemented to satisfy goals related to safety, level of service, project delivery, and long-term investment strategies. Once implemented, it is reasonable to expect that geotechnical asset management activities would support the transportation asset management focus areas. However, a key aspect that may differentiate geotechnical asset management for FLMAs is the broad range of stakeholder values that must be considered. For example, environmental, social, economic, cultural, aesthetic, and historical values are routinely incorporated in the transportation planning activities by each FLMA. Further, these values likely have an importance that is greater than a typical state department of transportation project. As a result, geotechnical asset management implementation in FLH must consider a broader range in performance criteria. *This is not a barrier to implementation.* Identification of performance goals is a critical component of asset management and it is possible to structure a geotechnical asset management program to support specific agency performance goals. The specification of goals is more important than the nature of the goals. An example geotechnical asset management program for FLMAs is presented in Chapter 5.

Asset Management Needs of Individual Agencies

The FLH program assists several agencies in project planning and delivery. These agencies include the NPS, U.S. Forest Service, USFWS, and Indian Reservation Roads. To the extent transportation asset management is supported for each of these agencies, geotechnical asset management can be a value added service. The highest degree of success for each individual agency is the achievement of their defined performance criteria.

As an example, the NPS is responsible for 397 park properties throughout the country with the mission of "…caring for special places saved by the American people so that all may experience our heritage." Conversely, the Forest Highway program consists of 29,000 miles of roads that are for the use and development of the National Forest. The performance goals of each agency are different, which must be addressed in the application of any asset management effort. Furthermore, within each agency different performance criteria likely exist due to the different missions for each NPS property, Forest Highway, or other FLMAs.

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CHAPTER 3 — COMPONENTS OF A GEOTECHNICAL ASSET MANAGEMENT PROGRAM

Asset management involves the collection and storage of inventory and condition data followed by analysis to support maintenance and project development decisions. To maximize the effectiveness, these analyses should be completed with consideration of the agency performance goals and as part of the transportation asset management plan. Typical performance goals in transportation asset management include managing life-cycle costs to optimize total operational lifetime expenditures, maintaining a defined level of operational service, and sustaining required and/or expected levels of safety for the travelling public. The performance measures that are established for these goals are expected to vary by agency, corridor, or geography.

For FLMAs, the goals also may include maintaining cultural, social, or historical values and providing access to public lands or parks. Regardless of the potential performance measures, the process of transportation asset management can be applied to the management of geotechnical features.

IMPLEMENTATION DISCUSSION

To develop the basic components of a geotechnical asset management program, it is important to evaluate the challenges to implementation, as discussed below:

Agency Goals and Policies

The initial process for the successful implementation of any asset management program is the understanding of agency goals and having the policies that facilitate and support implementation. For example, pavement asset management programs typically have a goal to maintain certain percentages of pavement in specified condition ranges, such as good, fair, or poor. Depending on the agency, these pavement condition goals are established by a transportation commission or executive management team that is responsible for the overall agency direction and success. Pavement condition goals and policies that support the regular tracking of performance measures is a critical process within the life cycle of the pavement asset management program.

In agencies with existing asset management programs, these goals provide the basis for the value of supporting programs. Further, the agencies have programmatic support through policies and procedures that allow for program development and implementation. To demonstrate the value of a geotechnical asset management program in the context of agency goals, the range of impacts from geotechnical features can be presented in the context of a benefit-cost analysis that illustrate the cost impacts throughout the life cycle. These impacts can range from minor pavement distress and loss of mobility as shown in Figure 8 (see the section *"Examples of the Value of Geotechnical Assets"* (page 6)), or even fatalities. Furthermore, these impacts can be sudden when compared to gradual deterioration rates for other transportation assets (e.g., pavements, signs) and also may have political and publicity concerns when economic damage occurs.

Figure 8. Photos. Examples of mobility loss and pavement distress from landslides.

Geotechnical Asset Management Approach

Many agencies have rockfall management programs that could be classified as geotechnical asset management efforts; however, the number of programs for other geotechnical features, such as retaining walls or landslides, is limited. While 25 transportation agencies now use some version of a rockfall hazard rating system, the adoption of these methods has been a steady process for nearly 20 years, with Montana Department of Transportation being the most recent agency to implement a rockfall hazard plan only as recent as 2005.

Based on the timeline for widespread rockfall hazard program adoption and a continued strain on infrastructure funding, a similar timeframe could be required for the widespread adoption of asset management strategies for many of the other geotechnical features presented in Table 2. Further, each of these geotechnical features would eventually need to be incorporated into the larger transportation asset management process, which eventually will include risk and cost benefit analysis.

An alternative approach may be warranted, based on the likelihood that a significant staff commitment is required to establish an asset management process for several independent geotechnical features. As presented in Perry and others, *cuttings* (2003), Perry and others, *embankments* (2003), Kelly and others (2005), and Scott (2011), when managing the potential for geotechnical failures, it is important to direct resources towards the features that have the greatest contribution to risk. While the NPS WIP provides valuable data on the inventory and condition of almost 3,500 retaining walls within 32 National Parks, Monuments, Recreation Areas, Parkways, and Seashores, the level of inventory and condition detail may be greater than required for walls that present a relatively low risk to the performance measures. For example, the roadway approach for many of these retaining walls may include embankments or rock slopes subject to landslides and rockfall or bisected by culverts. Depending on the performance measures (e.g., safety, mobility, and environmental preservation), failure of the embankments and rockfall could present a greater performance risk than the retaining wall failure. In this situation, a detailed inventory assessment of the wall exists; however, the management of geotechnical risks to roadway performance is incomplete.

A solution for this condition may involve initiation of geotechnical asset management within a corridor or route management program, where several geotechnical features are grouped into a single asset class that is then incorporated into existing transportation asset management programs. The approach is based on the two-tiered strategy presented by Perry and others, *cuttings* (2003), Perry and others, *embankments* (2003) and Scott (2011) and the risk management approach in AGS (2000). An advantage of this approach would be the allocation of resources in a manner that can initiate the risk reduction process without having to first complete a detailed inventory and condition assessment for each geotechnical feature. As presented in Scott (2011), any risk evaluation (and the resulting management plan based on the analysis) will have low value or incorrect conclusions if a complete evaluation of the failure modes is not performed. Because risk assessment is a fundamental process of transportation asset management, it is important these assessments be completed ***correctly*** for the value of geotechnical asset management to be recognized.

The use of asset classes (groups of similar assets) is documented in asset management programs for other infrastructure types. For example, Colorado Springs Utilities combines features into asset classes such as underground transmission, storage, and valves (Totman, 2010). Therefore, both tunnels and underground pipes are evaluated within the same asset class. For Colorado Springs Utilities this provides a simplified means for allocation of operation and maintenance costs while reducing the assessment and analysis burden. The creation of an asset class allows the opportunity to ***simplify the asset management process by focusing on the function of an asset*** rather than just the type. The assignment of features into an asset class for transportation asset management should be dictated by operational goals and risk tolerance for each agency. For example, rockfall sites often present a hazard to traveler safety while stability of retaining walls will influence the operational goals of a corridor. In this example, the agency may group the rockfall sites into an asset category related to safety goals, while the retaining walls are grouped into an asset class that manages the operation functions of the highway.

Data Management

A fundamental component of asset management is availability and reliability of data used in the analyses that guide funding and operational decisions. The purpose of data management includes efficient collection, storage, access, and visualization or distribution to stakeholders. The collection of data is a critical path process for asset management as analysis and qualitative and quantitative based decisions cannot occur until data are obtained. Additionally, incorporating available data as well as associated programs into the asset management plan should prevent duplication of effort that can result from dispersed data sources.

The transparency of data also is vital to the success of asset management. As discussed in in the section *"Data Availability and Management"* (page 20), there can be multiple data management systems within an agency. While these data have value, the success of asset management is diminished when the information is not shared or accessible. This separation of data systems can be equivalent to ignoring certain assets or features in the assessment process, as well as failing to realize how assets and their fiscal management may be dependent upon one another.

The quantity and type of data to be collected should be considered when establishing a geotechnical asset management program. Ideally, input of data is performed using electronic tools (laptops, tablet computers) in the field that are able to reference the position into the agency location format (e.g., Global Positioning System coordinates, RIP mile points). The data collection process should be designed based on the information required to support the asset management program. While there can be a tendency to record detailed observations on various features, this also can be an inefficient use of resources should the data not be used.

The collection and maintenance of inventory and condition data could be a challenge for an emerging geotechnical asset management program, and may be the limiting factor for implementation in an agency that lacks a well designed and centralized geographic information system (GIS) or other database tools. As shown in Tables 1 and 2, there are several geotechnical features that could be incorporated into geotechnical asset management. If a transportation agency commits to asset management of several features as standalone elements, separate data collection, management, and analysis programs may be required for each feature. This can lead to further separation of data and ineffective asset management. *The recommended solution for incorporating data management into asset management programs is through the use of enterprise systems that centralize, maintain, and make available all data to users within the agency.*

DATA COLLECTION IN SUPPORT OF GEOTECHNICAL ASSET MANAGEMENT

Comprehensive Inventory Approach

As discussed in the section *"General Strategies for Geotechnical Asset Management"* (page 15), there are different approaches for inventory and assessment of geotechnical features, which include a specific geotechnical asset type such as rockfall sites or retaining walls, or a tiered approach that considers a collection of geotechnical features. For a specific or individual asset type, there are established systems for the collection of inventory and condition data for features, such as rockfall hazards, retaining walls, and unstable slopes. For these features, a considerable effort by others has been directed at establishing the criteria and best practices for data collection. In general, the data collected under these programs include physical location, relation to roadway, type of structure/feature, feature geometrics, photographs, generalized descriptions, distress extent-severity-urgency, performance history, and subjective hazard ranking.

Multi-Tier Inventory Approach

With respect to a multi-feature tiered approach that incorporates risk assessment, the methods of inventory collection exist but appear to have limited implementation for transportation infrastructure within the United States. To perform risk screening after collection of the initial data (first tier), the recorded information must identify either or both the probability or consequence of a hazard (Perry and others, *cuttings*, 2003 and Perry and others, *embankments*, 2003). This will allow for a comparison of the relative risks between different features. Perry and others, *cuttings* (2003), Perry and others, *embankments* (2003) and Scott (2011) present a detailed discussion regarding data collection practices in support of risk screening methods. The general approach involves identification of the type of potential failure or geotechnical feature; the location, which includes both physical coordinates and relationship to the roadway (i.e., travel lanes, shoulder, beyond right-of-way); and a judgment of failure probability and consequence. During the initial tier phase, the probability and consequence evaluation is completed using broad categories that are qualitative in nature and generally represent ranges on the relative order of magnitude.

After the initial tier of data is collected, a risk register is established and the features with high probability for failure and a significant consequence are identified for subsequent analysis in a second tier. For the second tier analysis, the data collection needs can range from minimal additional needs to more thorough data inventories similar to those described in the section *"Comprehensive Inventory Approach"* (page 26).

Throughout this process, the baseline and desired performance goals should be considered to determine if a level of hazard or risk reduction is warranted. While the data collection effort will identify a range in relative risk, there also should be an assessment to determine if the existing conditions are at an acceptable performance level or goal, or if a different risk level (less or greater) is fiscally or operationally preferred. This is an important consideration that can estimate the anticipated costs to move an asset to a lower overall risk level over time and support decisions for repair or mitigation measures. As an example, Anderson and DeMarco (2012) discuss establishing a design standard for rockfall projects as a means to efficiently allocate resources based on corridor appropriate performance objectives and avoid "worst-first" management and over-/under-design of new or rehabilitated slopes. This concept can be illustrated by considering a FLMA corridor through several miles of canyon with multiple rockfall sites. In this scenario the use of a rockfall shed below a single rockfall site in the corridor would significantly reduce or eliminate the risk to safety and mobility at a specific location. While the risk is significantly reduced at this location, there are several other slopes with high hazard and risk levels, potentially including the approaches to the shed. By directing project funds to obtain a disproportionately high risk reduction at one location, the overall corridor risk may not be measurably reduced.

TIME-DEPENDENT CONSIDERATIONS

As discussed in the section *"Transportation Asset Management Overview"* (page 4), asset management is a continual process that involves collection of data, analysis, and improvement through repair or reconstruction in accordance with performance measures. The reliability of geotechnical features will change with time as will the agency performance goals. Additionally, risk also can change with time because of changes in natural or operational conditions, such as forest fires, availability of maintenance funds, or increases in traffic volume. Perry and others, *cuttings* (2003), Perry and others, *embankments* (2003), and United Kingdom Department for Transport (2003) present a process where the first phase of a two-tier assessment and risk evaluation is performed at regular intervals as a means of screening, identifying new hazards, and updating the risk register as improvements occur. The updated risk register can then be used to re-prioritize sites for more detailed quantitative assessment and improvement. A secondary benefit of the recurring assessment process is the collection of additional data to define the performance or deterioration of geotechnical features and validation and adjustment of probability values used in the risk analysis. For example, more reliable deterioration curves can be developed with time. As discussed in the prior section, screening with consideration of the performance goals is a necessary step to maintain an efficient program that direct resources where they are most needed.

Instrumentation and detailed measurement of the performance of specific geotechnical features also have been used to estimate life cycle performance. Typically, this is performed for sites with the greatest risk or actively experiencing failure. On the basis of a two-tier approach, where the second phase of analysis is quantitative, the use of instrumentation based monitoring may be warranted to improve the reliability of failure models. Additionally, monitoring can provide an early warning capability for the failure of a critical feature.

ESTABLISHING GEOTECHNICAL PERFORMANCE STANDARDS

Performance of Geotechnical Features

Per AASHTO (2011a), asset management focuses on business and engineering practices with the purpose of better decision making based on quality information and well-defined objectives. Therefore, the establishment of performance standards (objectives) is a critical process in asset management. The establishment of performance standards for geotechnical features is not commonly performed; however, the need exists (Stanley and Pierson, 2011; DeMarco and others, 2010; Bernhardt and others, 2003; Perry and others, *cuttings*, 2003; and Perry and others, *embankments*, 2003). In support of performance standards for geotechnical features, desired levels of service and service life must be included in the plan development.

For incorporation into a transportation asset management program, performance standards for geotechnical features or an asset class must support the overall agency goals. In a mature asset or performance management process, this requires direction from policy makers and implementation from the technical discipline leadership. Performance indicators in transportation asset management should be quantitative values and may include safety, mobility, and maximizing the life cycle of features for a minimum cost. FLMAs may desire additional performance indicators such as cultural preservation or environmental sustainability due to the unique missions of the different agencies. Additionally, the performance indicators can change through the life-cycle and will vary between different infrastructure owners.

In 2008, Wyoming Department of Transportation (WYDOT) initiated a transportation asset management program that is based on corridor needs to optimize service life while minimizing life-cycle costs and improving safety. The performance indicators in support of this program are system preservation, safety and mobility, and the individual construction and maintenance projects that support these goals must be defined in a manner that considers cost-benefit (Kidner, 2012). For example, a rockfall mitigation project may be classified within the safety category and will need to demonstrate a measurable benefit of risk reduction versus the required funds. ODOT asset management performance measures include safety, mobility/economy, preservation, sustainability, and stewardship (ODOT, 2012). Similar to WYDOT, the planning for projects and maintenance is directed towards satisfying these agency performance goals.

Development of Geotechnical Performance Standards

In an asset management program, the performance standards for geotechnical assets should be based on the agency performance measures. These standards may also be defined based on whether geotechnical features are managed as individual assets or grouped into a single asset class. On the basis of example agency performance measures discussed in the section *"Performance of Geotechnical Features"* (page 28), general performance requirements for geotechnical assets may include the following:

- Protect the safety of the travelling public.
- Maintain mobility of traffic.
- Achieve the target design life for the lowest cost.
- Prevent damage to the environment, adjacent property, aesthetic values, and cultural features.
- Minimize economic harm.
- Reducing the occurrence of emergency expenditures and non-forecasted failures

The Alaska Department of Transportation and Public Facilities is conducting research to develop performance standards for slopes (Stanley and Pierson, 2012a and 2012b). Other than this work, there are limited examples of established performance measures for geotechnical features in the context of asset management. Conversely, there are numerous methods for monitoring the performance of geotechnical features. While these methods are valuable to the geotechnical practitioner, the data are likely to detailed or not relevant when formulating a geotechnical asset management plan in accordance with agency goals.

For example, pavement management practices have been adopted by many municipal, state, and federal transportation agencies and are one of the original asset management program types. Similar to geotechnical features, the performance of pavements can be measured using several criteria such as condition, distress manifestation, roughness, ride comfort, skid number, rut depth, and deflection values. However, pavement smoothness is the key element of perception of the travelling public (ODOT, 2012). Therefore, the only performance measure for the pavement asset in ODOT is the percentage of pavement with a rating of fair or better, which is the middle category of a five part rating system (very poor, poor, fair, good, very good). ODOT does use different methods to assess pavement condition based on roadway type but all results are normalized and reported into the five potential classifications. This practice is common among many federal, state, and municipal transportation agencies.

A similar practice could be implemented for geotechnical assets. The poor performance of the geotechnical features presented in Table 2 can lead to pavement damage which results in a negative perception from the travelling public. Using the performance criteria developed for pavement management, a proposed geotechnical performance indicator could be defined as the percent of pavement that is reduced to below the fair category as a result of a given geotechnical feature.

As presented the section *"Examples of the Value of Geotechnical Assets"* (page 6), the failure of geotechnical assets can have a significant and sudden impact to other transportation assets or performance metrics. This characteristic is unique to many geotechnical features when compared to other asset types. For example, the failure of a pavement typically will not damage adjacent property, sign structures, or bridges. Pavement failure also typically will progress over a long duration that allows traffic and the agency to adjust to the deterioration. However, a landslide or retaining wall failure can damage pavements, utilities, property within and beyond the right-of-way. Further, these geotechnical features can fail suddenly or over a short period and impact level of service and regional economies. To address these situations, an agency could establish a ***performance measure*** for a corridor or system that *specifies minimum allowable traffic volumes, the maximum time that a road closure is acceptable, or number of acceptable emergency failures*.

Based on the potential for abrupt impacts to transportation infrastructure, geotechnical asset performance indicators, as previously noted, may also include safety, mobility or economic values, and any sustainable measures related to environmental, cultural, or aesthetic damage. The selection or importance of these performance criteria will ultimately depend on the performance measures of the transportation agency; however, they should be incorporated when applicable. As an example, an ODOT safety performance measure is the number of traffic fatalities per mile traveled. To the extent that a rockfall site may contribute to this performance metric, the geotechnical asset management plan can be used to identify candidate sites for the mitigation projects that provide the greatest reduction in fatalities per mile. Currently, the consideration of roadway safety performance metrics is a non-traditional practice for design and maintenance of geotechnical features. However, the standard geotechnical practice does routinely evaluate event frequency and the areal extent of features, and it is feasible to perform additional analysis that can make a correlation to asset management performance metrics.

While establishment of performance measures is required for implementation of geotechnical asset management, the process is likely already performed for other asset management programs and can be easily adapted.

ASSET PERFORMANCE ANALYSIS

Asset performance analysis is required to efficiently manage of geotechnical features throughout a life cycle. As discussed in the section *"Life-Cycle Performance Considerations"* (page 10), and presented in Figure 5, pavement management systems use deterioration (relative condition) curves for tracking and forecasting condition levels based on the degree of ongoing rehabilitation investment. While this approach could be applied to geotechnical features, it may be difficult to implement at the early stages of a geotechnical asset management program because of limited prior performance data.

Forecasting asset performance on the basis of a condition or deterioration curve requires reliable data. For geotechnical features these curves have not been developed and there appears to be limited research on the topic. With the implementation of a geotechnical asset program, the data to create deterioration curves could be compiled with time. Once developed, these curves are anticipated to vary between features and also within a grouping of the same feature. Much of this variance is due to the greater uncertainty associated with natural systems. Concrete and asphalt for a roadway are constructed with quality control processes and the variability of these material properties is substantially less than those found in the natural environment. The variability in natural systems will likely produce a greater range in potential condition curves. This concept is presented on Figure 9, which is modified from Totman (2010).

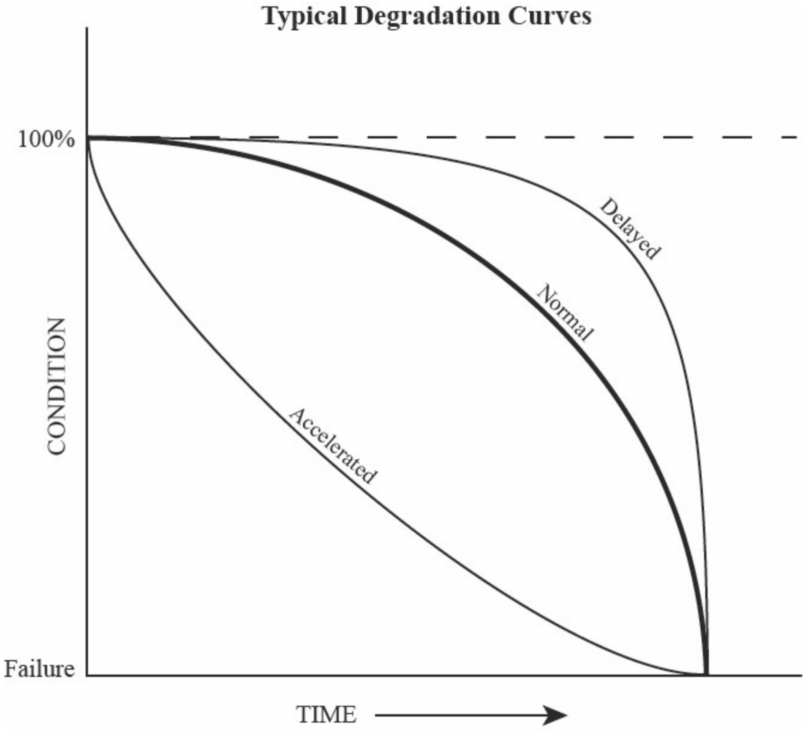

Figure 9. Plot. Potential variability of deterioration curves for an individual feature type.

An example of the uncertainty related to deterioration of geotechnical features would be the deterioration of rock slopes within the same corridor, which will vary on the basis of rock type, microclimate, vegetation, and exposure resulting in a deterioration curve unique to each site. A similar uncertainty in deterioration could be observed for different retaining wall types, such as mechanically stabilized soil or cast-in-place concrete walls, requiring different deterioration curves. Figure 10 presents a theoretical range in deterioration curves for three different feature types within a single geotechnical asset class. It must be recognized these figures are provided for illustrative purposes. The deterioration of geotechnical features is expected to vary significantly and may not follow a curvilinear shape. As illustrated by these examples, the creation of reliable deterioration curves for use in forecasting the performance of different geotechnical features is a significant task that would require considerable time and investment, particularly at the start of the asset management process.

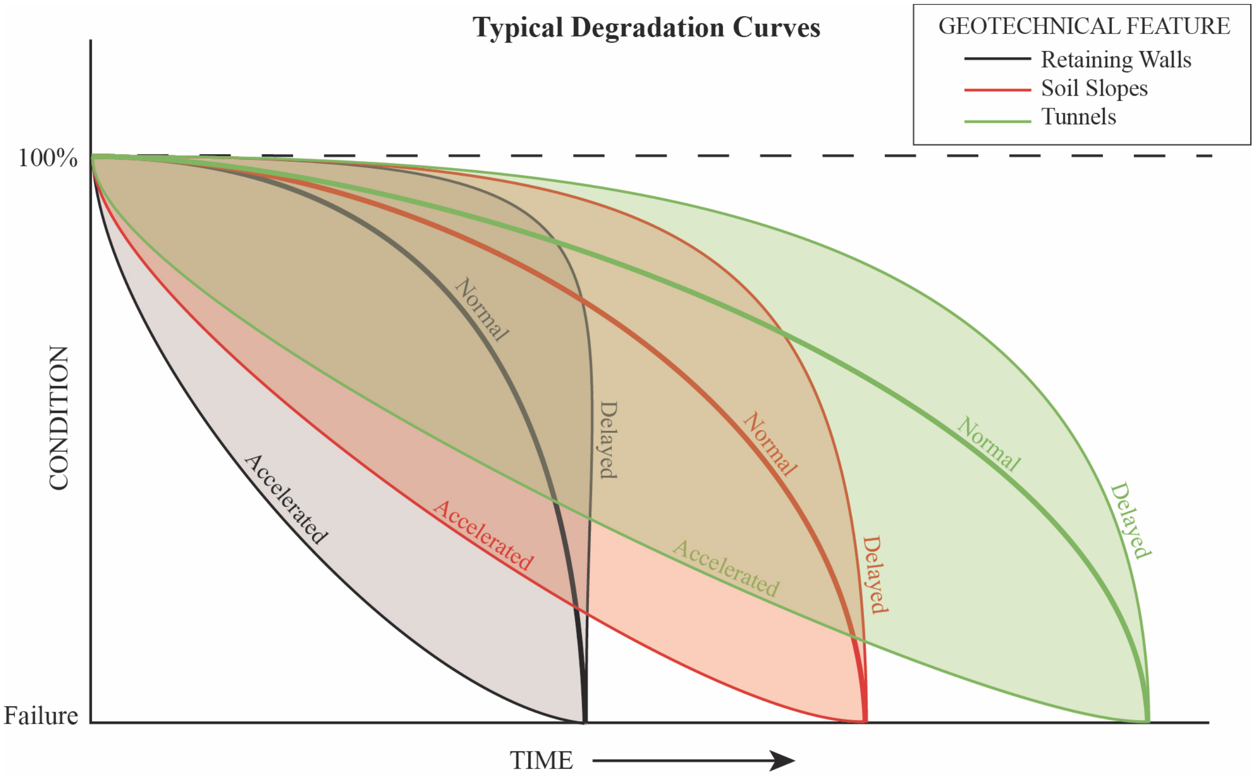

Figure 10. Plot. Combination of deterioration curves for different geotechnical features.
(Note: This for illustrative purposes only and may not represent actual trends).

Because of the investment and time required to develop condition curves, the use of risk analysis and multi-tier assessments with a screening process may be a means for a more reliable method of evaluating maintenance, rehabilitation, and replacement strategies in asset management. This approach is supported by Perry and others, *cuttings* (2003) and Perry and others, *embankments* (2003). The established practice of geotechnical asset management in the United Kingdom is based on risk and assessment procedures to evaluate current conditions and forecast performance until the next assessment. At that time, a new risk register (as discussed in the section

"Geotechnical Asset Management Approach" (page 24)) is developed and project prioritization can occur. Perry and others, *cuttings* (2003) and Perry and others, *embankments* (2003) propose that the period between assessments be determined from the findings of the initial risk assessment. The United Kingdom Department for Transport (2003) presents a method for reassessment every five years. Additionally, Scott (2011) indicates that risk screening can be completed whenever there is a need to prioritize activities. This approach assumes screening is performed with qualitative or semi-quantitative methods that are relatively simple to perform. After each screening, quantitative analyses are performed on the features that are in the highest risk category. To illustrate this concept, Figure 11 shows how a regular assessment and risk screening effort could be used to preserve the condition of multiple feature types within the same asset class. For the example presented in Figure 11, it is important to note the non-critical feature does not require improvement until considerably later in the life cycle.

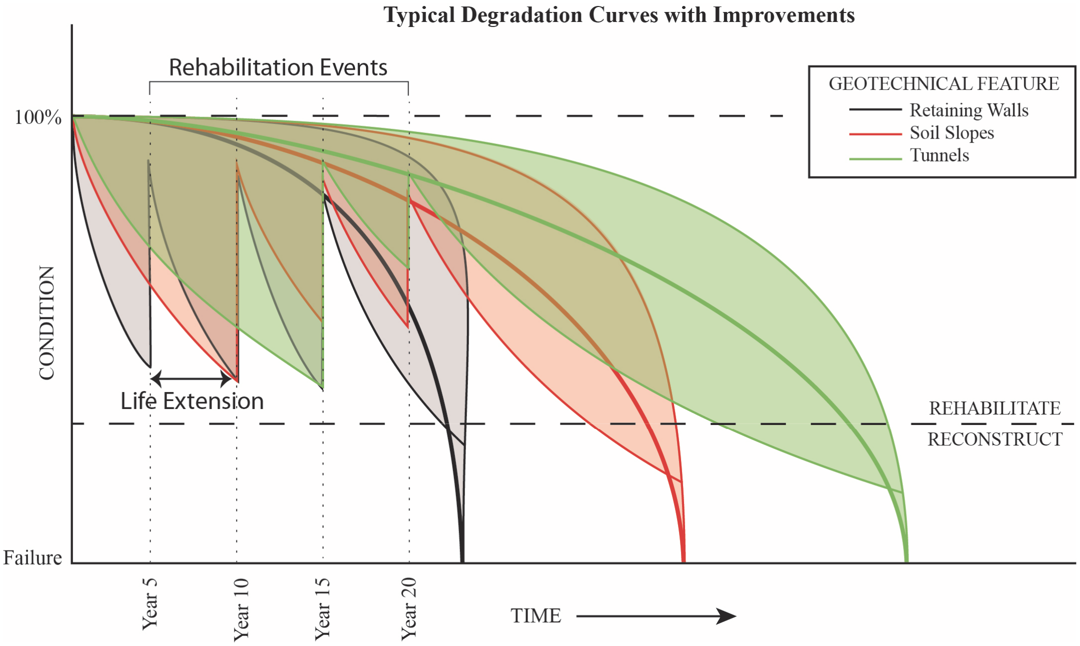

Figure 11. Plot. Example deterioration curves for multiple geotechnical features in a single asset management classification.

As an asset management program proceeds, the confidence in risk values should increase and it may be possible to use risk values as a guideline for decision actions depending on performance expectations. The literature presents examples for acceptable failure probabilities that could be compared to the results of quantitative analyses from the second tier of risk screening. However, the selection of risk criteria should be performed by each agency on the basis of performance goals. It expected that the tolerance for financial and safety risks will vary by agency and owner.

The performance analysis will provide a basis for benefit-cost consideration in project prioritization to ensure funds are allocated in a manner that satisfies performance measures such as safety, mobility, and preservation. An important consideration in the analysis is the as-low-as-reasonably-practicable (ALARP) principal. The ALARP principal is discussed by Scott

(2010), Perry and others, *cuttings* (2003), and Perry and others, *embankments* (2003). This principal provides for mitigation efforts to be undertaken when the cost of risk reduction is not disproportionate to risk.

CHAPTER 4 — CURRENT STATE-OF-THE-PRACTICE

The practice of transportation asset management is a proactive means to manage agency assets based on desired performance goals for the lowest cost over the life-cycle or performance life. Based on this definition, there does not appear to be a standard of practice for geotechnical asset management within state and federal transportation agencies in the United States. There are agencies that have inventory programs for geotechnical features, such as rockfall sites, tunnels or retaining walls, which could be considered the initial stages of an asset management program.

Of the existing examples of management programs for geotechnical features, the current practice consists of agency wide programs rather than corridor level programs. Recently, WYDOT initiated a transportation asset management program based on transportation corridor regions rather than a single statewide program (Kidner, 2012). The purpose for this corridor approach is the recognition that different corridors within the state have different needs or performance expectations.

Rockfall sites are managed through a rockfall hazard rating system for at least twenty-five transportation agencies and this feature exhibits the most progress towards a standardized management practice. For the remaining geotechnical features (see Table 2) that could be included in an asset management plan, there are limited examples of a formalized management program within state and federal transportation agencies. ODOT includes tunnels, unstable slopes, and retaining walls in the statewide transportation asset management plan and is currently in the process of developing the inventory data for walls and slopes. The WIP data for the NPS is incorporated into Facility Management Software System and has been used for minor repairs, maintenance, and project planning (DeMarco and others, 2010). The Alaska Department of Transportation and Public Facilities has initiated a geotechnical asset management program that is planned to include management of unstable slopes, material sites, retaining walls and embankments. Of this program, the unstable slope and material site management programs are underway, inventorying of retaining walls has begun, and the embankment management program is in conceptual development.

For rockfall sites within the United States, the majority of the management process has been directed at hazard management with no known applications of risk management on a corridor or agency wide basis. These programs are generally focused on inventory documentation, hazard identification, and qualitative rankings or judgment as a means of prioritization. There are international examples of risk analysis for rockfall or other slope hazards (AGS, 2000 and Jaiswal and others, 2010).

For the FLMAs, there are road inventory and bridge inventory programs for the NPS and USFWS, as well as the WIP for the NPS. Other than tunnels in the bridge inventory program, geotechnical features are not incorporated into these systems.

In general, there are limited case histories of incorporating risk analysis for individual features or normalization of risk values among different geotechnical assets within US transportation infrastructure. For most geotechnical features along a highway, the practice of asset management has been directed at ***hazard identification rather than risk analysis***. Hazard identification typically consists of characterization of the geotechnical feature, extent, and potential area at risk. While the some rockfall hazard rating systems incorporate subjective risk values, the analysis is limited to a score value rather than a probability. Consequence is not directly scored (e.g., consequences of a road closure due to rockfall). Therefore, the risk (product of probability and consequence) is not quantified in a manner that an agency can compare to a desired performance measure, such as number of injuries per vehicle mile traveled.

Several municipal, state, and federal agencies are performing transportation asset management as presented in AASHTO (2011a). While these agencies define performance measures such as safety and mobility for the asset management program, there does not appear to be widespread incorporation of geotechnical features as an asset class. Through personal communication with planning staff from the FHWA Central Federal Lands Highway Division and state transportation departments, there does appear to be a need for geotechnical asset management; however, personnel and financial resources are limited.

CHAPTER 5 — DEVELOPING A GEOTECHNICAL ASSET MANAGEMENT PROGRAM

Per AASHTO (2011a) an asset management plan includes the following components.

- Data management,
- Inventory and condition surveys,
- Levels of Service,
- Service Life,
- Performance measures and condition indices,
- Risk management,
- Life cycle and benefit and costs analyses, and
- Decision support.

To illustrate the value and structure of a potential geotechnical asset management program, the following example is provided for a typical two-lane paved roadway under the jurisdiction of a FLMA. When developing this example program, the plan was formulated to minimize staff and resource commitments through the use of risk assessment concepts. When developing asset management plans, an agency can unintentionally direct limited resources towards the inventory and assessment of hazards, which may misdirect effort to features that are not critical to the performance goals. This potential for misdirection of resources may be reduced by incorporating risk concepts early in the plan development.

The road in this example provides an economic benefit to the region and connects communities within and beyond the managed property. Within the transportation corridor, there are a range of geotechnical features that include rockfall sites, landslides, tunnels, retaining walls, large diameter culvert crossings, engineered and reinforced rock slopes, and embankments. The processes for the proposed geotechnical asset management plan are presented in Figure 12 and discussed below.

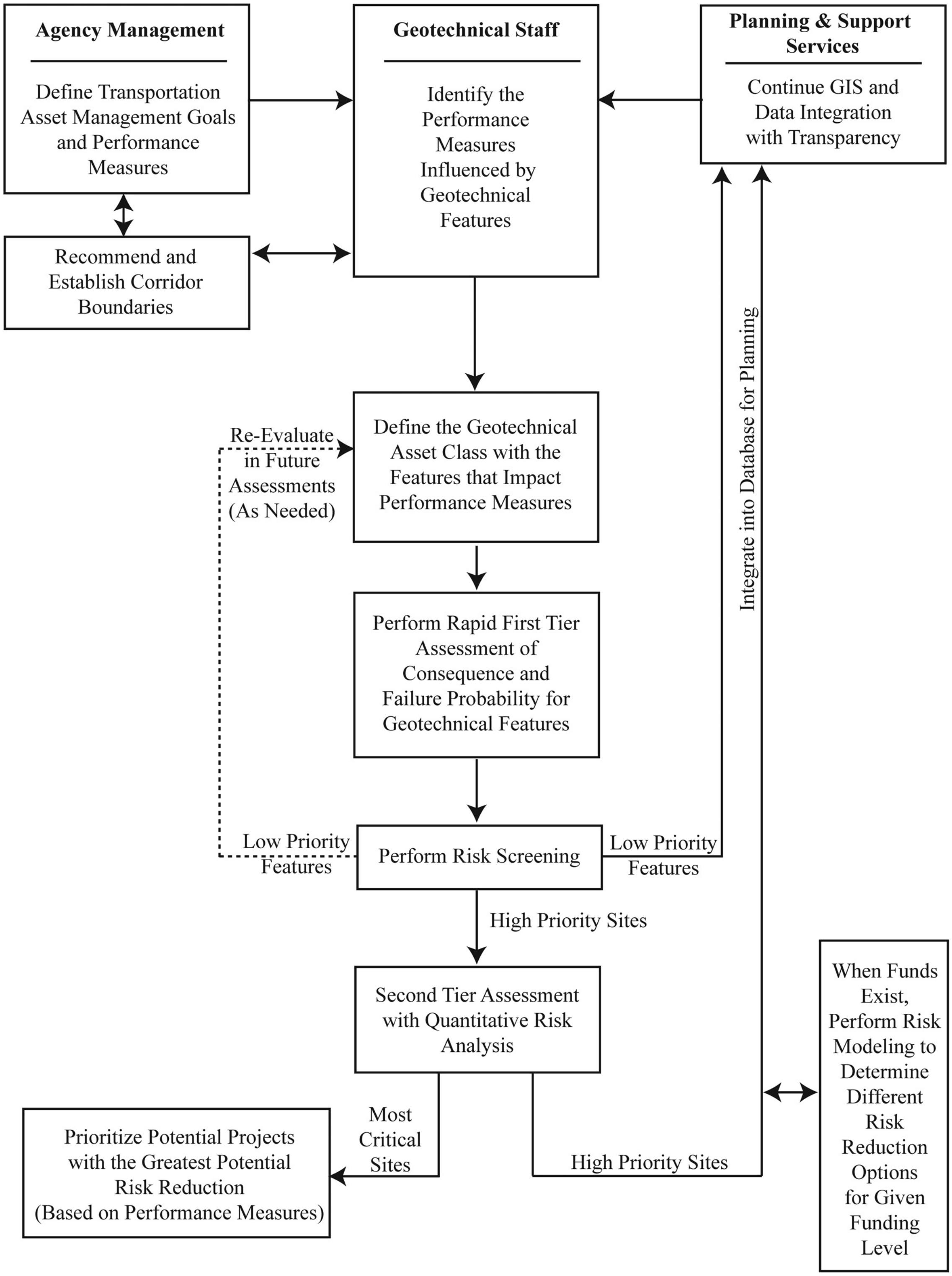

Figure 12. Chart. Proposed processes for a geotechnical asset management plan.

ESTABLISH PERFORMANCE MEASURES

Performance measures are a fundamental component of transportation asset management and the geotechnical asset management plan should relate to the agency performance goals as described in the section *"Development of Geotechnical Performance Standards"* (page 29). Ideally, the geotechnical asset management plan should support the agency transportation management plan if one exists. In the absence of an agency transportation asset management plan, geotechnical asset management could be implemented by discipline leadership and likely would still provide value.

The performance goals will be the basis for establishing quantitative measures of the geotechnical asset management plan. For the roadway in this example, the performance goals are safety, mobility, and preservation of environmental and cultural resources. Based on these goals, the proposed performance metrics are presented in Table 3.

Table 3. Performance goals and measures for example geotechnical asset management plan.

Agency Goal	Performance Measure	Quantitative Assessment Parameters
Safety	Fatalities	Fatalities per vehicle mile traveled
	Injuries	Traffic injuries per vehicle mile traveled
	Accidents	Number of accidents caused by debris on road or poor road condition (not weather or wildlife related)
Mobility	Closure	Number of hours of full closure per year
	Delay	Hours of travel delay per year
	Capacity	Number of hours permitted for lane blockage; percent of vehicles travelling at posted speed
	User Cost	Maximum allowable road user cost per year
	Economic Indicator	Corridor business survey score
Preservation	Pavement Condition	Number of locations with fair to poor pavement condition that is due to subgrade structure deficiency
	Cultural Resources	Number of cultural and historical resources at risk from geotechnical features
	Environmental	Percent of storm water discharge sites not in compliance
	Sustainability	Favorable cost/benefit ratio, considering tangible and intangible costs and benefits

Note: This is provided as an example only.

DEFINE THE GEOTECHNICAL FEATURES TO INCORPORATE INTO A SINGLE ASSET

While individual geotechnical features could be managed as separate assets, it may be more efficient to combine these features into a single asset class. Furthermore, as presented in Scott (2011), a critical process in risk management is identification of all potential failure modes; otherwise the results will have a low value or be incorrect. By grouping geotechnical features into a single asset class, it is possible to capture the extent that earth materials and processes may negatively affect the agency performance goals.

An alternative approach that is in development with the Alaska Department of Transportation and Public Facilities consists of managing different geotechnical features as individual assets and defining condition indices for each feature type (e.g., retaining walls, slopes, and embankments). The condition indices can then be combined into a geotechnical asset system health index, which is integrated into the agency transportation asset management plan (Stanley and Pierson, 2011 and 2012b).

For this example, the known geotechnical features consist of rockfall hazard sites, landslides, tunnels, retaining walls, large diameter culvert crossings, engineered and reinforced rock slopes, and embankments. Rather than perform separate asset management programs for each of these features, they will be incorporated into a single geotechnical asset class. When combining features into a single asset class, the inventory and analysis processes should be designed to focus on the critical features. This is discussed in more detail in the following sections.

PERFORM FIRST TIER ASSESSMENT

As presented previously, a multi-tier assessment process is used in other countries or infrastructure types. The basis for this approach is to identify those features that have the greatest contribution to performance risk and concentrate the available resources on these elements. This is in contrast to the practice used for existing rockfall or retaining wall inventory programs in which every site is documented and inventoried to the same level of detail before analysis is performed.

The goal of the first tier assessment is a basic inventory and condition assessment of the geotechnical features and to capture the consequences and/or probability of failure for each feature. The inventory should include descriptive information, such as type of feature, location, and evidence of failure or repair. The assessment should also evaluate the failure likelihood and consequence using qualitative methods. A more complex failure analysis can be performed on specific critical features later in the process.

A two person team is recommended for field inspection and assignment of qualitative scores. A two person team has a safety benefit during field work. Additionally, a multi-person review will reduce the potential that critical features are overlooked and can reduce bias during qualitative evaluation. The use of a team for field inspection is consistent with Scott (2011), Kelly and others (2005), Perry and others, *cuttings* (2003), and Perry and others, *embankments* (2003).

With respect to usage of staff resources, the assessment would be designed to use GIS methods for rapid data entry, storage and retrieval. Prior to field mobilization, the assessment team should review the available inventory data, such as WIP, RIP and BIP, as well as satellite and street view imagery. This information will provide a general assessment of the corridor and may reduce the amount of personnel time required for field inspection.

Ideally, the field data collection tools and process would be designed to collect the necessary information at a rate of 50 to 100 miles per day in both directions of travel. This assumes the geotechnical features are periodic along the length of the corridor. As presented in Ellis and others (2008), approximately 50 miles of levee embankment were inspected using a rapid assessment technique by one person over a ten day interval. This may represent the lower bound of production (5 miles per day) for traversing a corridor with complicated geological conditions with continuous features of interest.

A proposed inspection and failure assessment methodology is presented in Table 4. The general concept and terminology presented in the table are based on discussion provided in Scott (2011), Perry and others, *cuttings* (2003), and Perry and others, *embankments* (2003). The descriptions provided for failure likelihood and consequences are intended to approximate an order of magnitude difference between categories to generally approximate the risk. When performing the assessment, the inspection team also could subjectively estimate failure probability or use expert elicitation to approximate the failure potential between different geotechnical features.

Additionally, it is important for the assessment to describe the failure condition for each entry as some sites could have more than one failure scenario that affects an agency or corridor performance measure. For example, a rock slope above a highway can present a risk from a rockfall that might impact a vehicle. The geological structure of the same slope also may have failure modes that could results in a large rock slide that blocks the road and impedes an adjacent stream.

For the range of potential geotechnical features, rockfall sites likely will pose a higher relative risk when including fatalities in the consequence definitions. Mitigation of rockfall will generally address safety performance measures, while other geotechnical features may influence management of mobility and/or preservation goals. Therefore, an agency may need to consider a tolerable fatality and injury risk level when defining consequence criteria. Alternatively, a secondary screening assessment could be completed that considers only fatality consequences. Use of two separate consequence assessments (fatalities and infrastructure) may result in an improved integration of geotechnical features for typical transportation asset management performance measures.

Table 4. First tier assessment data collection needs example geotechnical asset management plan.

First Tier Assessment Parameter	Criteria	Explanation
Inventory	Type of Feature	Rockfall site, landslide, tunnel, retaining wall, large diameter culvert crossing, engineered and reinforced rock slope, or embankment
	Physical Location	Location referenced to existing agency GIS format
	Condition	Note approximate geometry and observations of distress.
	Relative Location	Roadway, Uphill or Downhill Shoulder, Within or Beyond Right-of-Way
Failure Scenario	-	Description of potential failure scenario. For example, the facing for the fill side retaining is deteriorating and resulting in soil loss. Progression of soil loss will undermine the roadway and could cause a sink hole in the travel lane.
Failure Likelihood	Very High	There is significant evidence failure has occurred or will occur without any further triggering events. The subjective probability would be near 0.99.
	High	There is evidence a failure will occur with only a minor triggering event. The subjective probability may be 0.9 for this category.
	Moderate	A failure could occur but evidence suggests the event could be either unlikely than likely. The subjective probability is near 0.5 in this category.
	Low	A probability of failure may exist but would require a remote circumstance to trigger failure. The subjective probability may be near 0.1.
	Unlikely	A series of remote and low probability events would need to concurrently occur to cause failure. A subjective probability value would be less than 0.01.
Failure Consequence	Level 0	Minimal to no impact to the corridor from a failure. The failure of the feature would be off the roadway and confined within the right-of-way or easement. A failure event may not require any immediate maintenance or repair.
	Level 1	The failure would have a minor effect to the roadway shoulders and require some degree of maintenance or reconstruction. The traffic speed may be reduced to accommodate the failure or repair activity, but travel lanes can remain open throughout the event.
	Level 2	A failure and/or repair would impact one lane of the road requiring a temporary onsite detour or lane closure for greater than one day. The event also may create negative publicity or short term economic effects for regular users of the corridor. The repair of this failure would likely involve non-agency maintenance or construction personnel.
	Level 3	The failure damages or blocks the entire road width and causes a full road closure for more than one day. Temporary stabilization or earthwork can reopen the road to restricted travel within a few days of the event, but a significant repair, reconstruction, is required to restore the roadway to pre-failure conditions. There is a likely potential for property damage to vehicles or adjacent private property as well as measurable economic loss to users and communities within or beyond the corridor. Additionally, there could be a temporary increase to the safety of traveling public due to poor driving surface, below standard detour alignments, and driver expectations.
	Level 4	The failure causes a prolonged road closure that could extend for weeks or months before temporary stabilization is performed. Significant economic effects result to the corridor and surrounding region. The financial burden of a permanent repair requires emergency relief funds or exceeds the available contingency budgets. During the event, there is a significant potential for fatalities.

COMPLETE RISK SCREENING

For the example corridor defined above, the data from the first tier assessment can be summarized in a risk matrix that evaluates the relationship between probability and consequence levels. An example risk matrix is presented in Figure 13. The matrix indicates that features in the upper right corner of the figure are more critical and pose the greatest geotechnical risk to the corridor, while the features in lower left corner may have a lower priority and do not require further assessment at this time. For the critical features, quantitative risk analysis is recommended to confirm the results of the screening and assist with mitigation option selection.

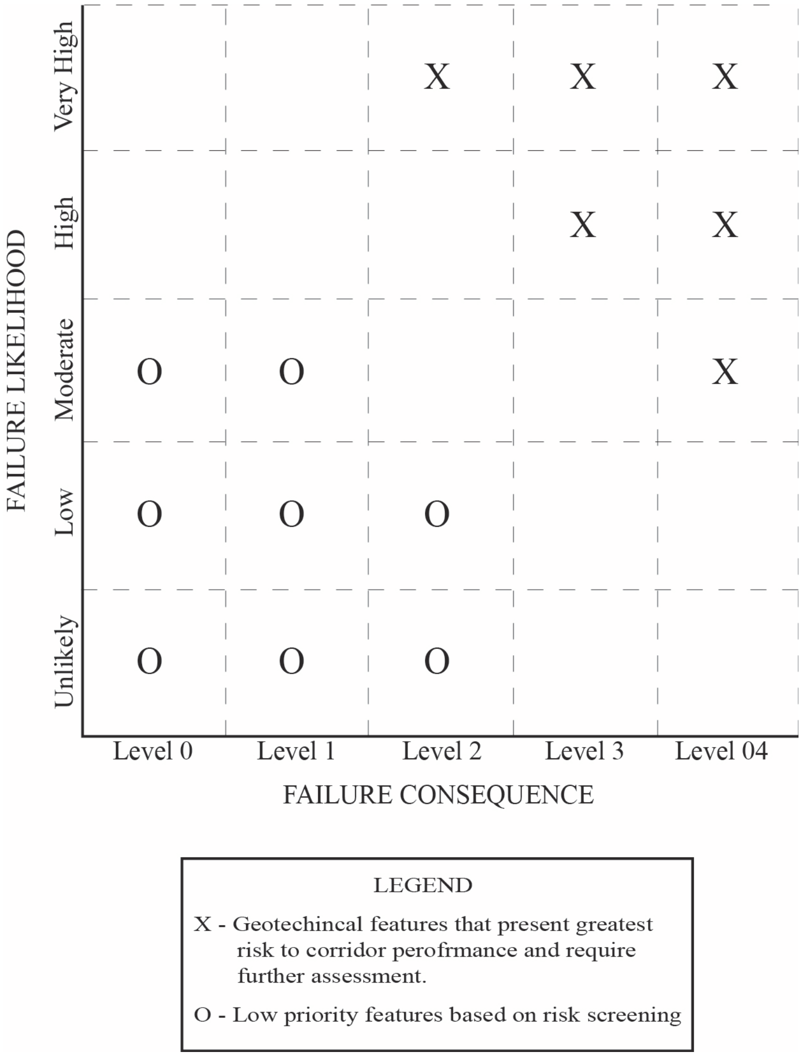

Figure 13. Graph. Example risk matrix for a geotechnical features in corridor.

Once risk screening is completed, an agency has an opportunity to identify or re-evaluate the performance standards based on the actual data trends. As an example, a theoretical risk screening matrix for all the rockfall sites within a transportation agency is presented in Figure 14. In this example, the likelihood of an event is estimated using probability related factors in the rockfall hazard database and traffic volumes are used as a surrogate for economic and safety consequences. The relationship between consequence and likelihood provides for a qualitative risk evaluation or screening. A figure such as this could be used to develop a rockfall performance standard that is based on the current conditions (performance) for a certain percentage of the slopes (such as 75 percent of the data set). Using this performance standard, the asset management plan would have a goal to move higher risk sites to satisfy this performance threshold while maintaining lower risk slopes at or below the standard. As discussed in the next section, additional analysis for the higher risk slopes can estimate the cost to mitigate each slope to the target performance standard. This process is ***an asset management practice that evaluates the total expenditures required for the greatest overall reduction in risk***.

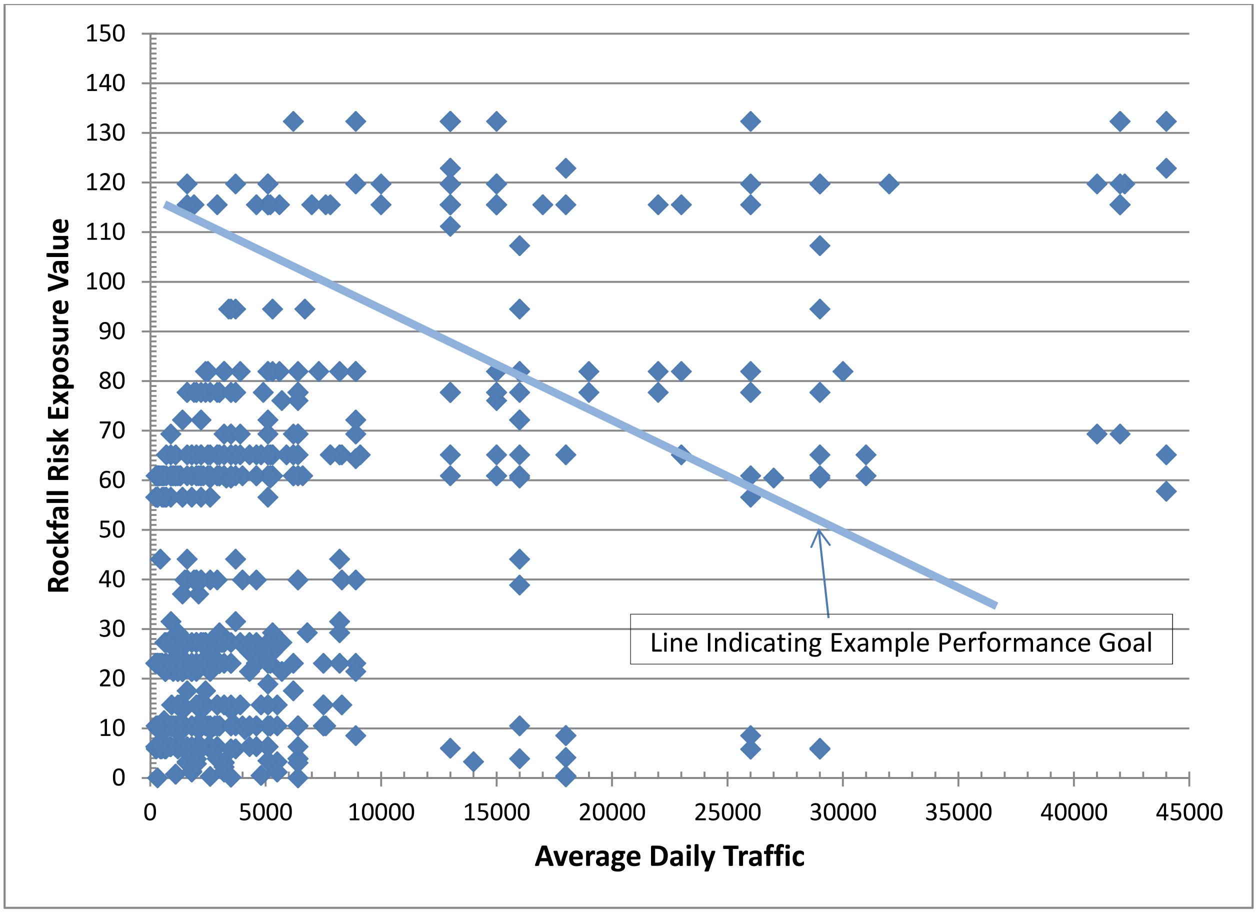

Figure 14. Graph. Example risk matrix for a rockfall features in corridor.

PERFORM SECOND TIER ASSESSMENT OF SPECIFIC FEATURES

After the risk screening process, a more rigorous quantitative analysis can be performed on each critical site identified in the corridor. Depending on the methods used and the degree of confidence in the data, it may be possible to complete the second tier of assessment without additional field inspection. The goals of this phase may include the following.

- Estimate quantitative risk values for additional screening processes.
- Determinate of the potential performance measure improvements in the context of transportation asset management goals, such as reduction in number of hours of travel delay.
- Prioritize projects in a constrained funding environment based on normalized risk values and value per dollar spent toward achieving the risk performance standard established for the route during tier 1 evaluations.

Quantitative Risk Screening

Quantitative analysis can provide a numerical value for the risk from a geotechnical feature that is a basis for measurement or comparison with other features. The topic of risk assessment and statistical approaches is beyond the scope of this document; however, there are examples of quantitative risk assessment in other asset management practices that would benefit from the multiple geotechnical features in this corridor example.

Using the failure scenario description from the first tier assessment, a decision tree can be generated to evaluate expected cost of a given feature, along with expected cost for various mitigation, improvement, or maintenance alternatives. The components for a decision tree in a geotechnical asset management program include the following.

- Determine the probability of failure based on the established practices such as:
    - Numerical models and objective analyses, such as slope stability models with a probabilistic assessment.
    - Use available historical data, such as number of rockfall incidents within a certain period or pavement maintenance records.
    - Use expert elicitation and subjective probability to estimate values.
- Determine the consequence of failure, which may be a more subjective process.
    - Estimate the tangible costs, such as the expense to repair road damage.
    - Estimate road user and economic impacts, such as traveler delay and lost revenues to businesses.

While methods for estimation of road user cost are established in pavement management practices, the evaluation of economic impact is less certain. As demonstrated in the section *"Examples of the Value of Geotechnical Assets"* (page 6), failure associated with geotechnical features can cause significant economic impacts within a region. Omission of these consequences will diminish the results of a geotechnical asset management plan. Methods of estimating economic impact that have been developed for consequences of floods, tornados, and other natural disasters may be adaptable to geotechnical asset management. However, in the absence reliable data or analysis of economic impacts, subjective criteria can be used as the basis for estimating intangible costs as presented below.

- Severe Damage – road is closed for several days to complete repairs: $1M.
- Moderate Damage – road is partially damaged and able to maintain at least one lane of traffic during repair work: $0.1M.
- Light Damage – Minor cleanup required and no lane closures or detours: $0.02M

An example of decision trees for a landslide, culvert crossing, retaining wall, and rockfall is presented in the Appendix. Additional decision trees could be generated for each critical geotechnical feature that is identified from the first tier risk screening. A summary of the qualitative assessment output for this example corridor is provided in Table 5.

Table 5. Quantitative risk assessment results for an example geotechnical asset management plan.

Feature	Action	Consequence	Annual Occurrence Probability	Cost for Year of Improvement	Expected Annual Cost After Improvement (if performed)
Landslide	No Improvement	Mobility: Long term lane loss Economic: Revenue loss for corridor Preservation: Pavement damage	40%	$870,000	$870,000
	Install Ground Anchors		1%	$3,021,750	$21,750
	Install Groundwater Drains		5%	$608,750	$108,750
Culvert Crossing	No Improvement	Preservation: Embankment failure Environmental: Sediment contamination in river	40%	$20,500	$20,500
	Culvert Cleaning		10%	$25,125	$5,125
	Culvert Replaced		1%	$100,513	$513
Retaining Wall	No Improvement	Preservation: Retaining wall and roadway damage Mobility: Temporary lane closures for repair	15%	$80,625	$80,625
	Maintenance Option A		10%	$103,750	$53,750
	Maintenance Option B		1%	$105,375	$6,375
Rockfall Site	No Improvement	Safety: Fatality and injury of public Economic: Litigation and public perception	90%	$663,750	$663,750
	Scale Slope		60%	$842,500	$442,500
	Scale Slope and Install Rockfall Fence		25%	$2,184,375	$184,375

It is important to note the values presented in Table 5 are approximations to support the geotechnical asset management program and the service life of the individual mitigation options would need to be considered for a life cycle analysis. The costs are not intended to be an accurate estimate of a repair. Rather, the costs are relative and indicate where the greatest geotechnical risk exists within the corridor. The relative costs should be used to support decisions for project planning.

While the scenarios in Table 5 are hypothetical for the purposes of concepts illustration, the results of an actual assessment could be expanded to show the magnitude and timing for return-on-investment on the basis of life cycle. Figure 15 presents this concept for the example rockfall site presented in Table 5. In this example, the more expensive mitigation option has a lower predicted annual cost that could result in significant savings that are dependent on the desired life cycle for the site. In this scenario, the savings could be significant enough to justify the initial expense and also recognize savings for improvements or risk reduction elsewhere in the corridor. It is important to temper the results of this type of analysis against the performance goals. For example, while a life-cycle cost analysis may support certain mitigation options, the agency also should consider if the resulting level of risk reduction is warranted. These qualitative risk assessment procedures can be combined for multiple features in a trade-off analysis that determines the greatest level of risk reduction over a specified life cycle and based on available funding scenarios

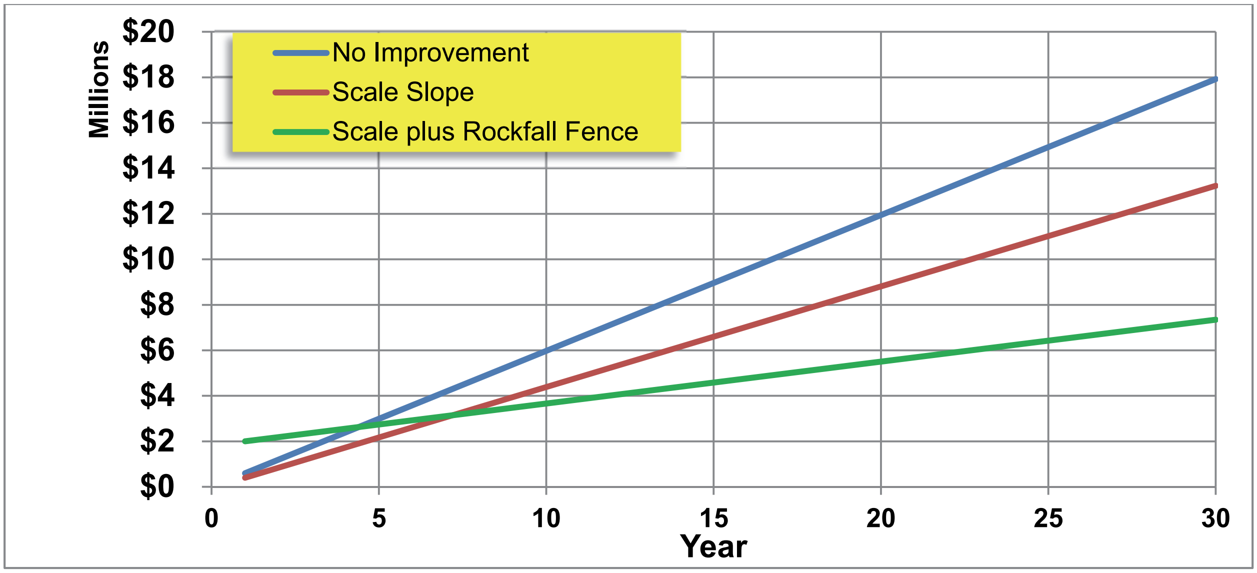

Figure 15. Graph. Example life-cycle analysis for rockfall site.

There will be uncertainty in any risk assessment process. If necessary, the results could be grouped by a confidence category. Scott (2011) presents a categorization scheme for good, medium, or poor confidence, which considers whether additional information would change the score.

Additional Risk Analysis Methods

A proven method for risk estimation from slope hazards is documented by the AGS, 2000. The method has been used for site specific landslide and rockfall risk analyses and can be expanded to incorporate other geotechnical features. Additionally, the results of the risk estimation can be normalized to compare the values between features within a corridor. This approach considers the elements at risk (property or persons), probability of the event as well as spatial impact, and vulnerability. The vulnerability assesses the probability of fatality during an event or the proportion of lost property value.

This method would produce a similar format of results as shown in Table 5. However, more parameters are required to complete the analyses, which could diminish the reliability of the results if there is low confidence in the data. Additionally, these methods are more thorough and may require more staff resources and analysis time. With respect to road user costs and economic risks, the decision tree methods may be more efficient. However, regardless of the analysis methods, it is important to track actual expenditures and risk reductions against the performance standards and compare to predicted conditions. Further, these processes need to consider service life differences between different mitigation measures.

The AGS (2000) risk analysis method may be more applicable in situations where the agency asset management performance measures require an estimation of fatality risk. As discussed above, rockfall sites likely will present the highest safety risk relative to other geotechnical features. Furthermore, the economic risk of a rockfall is often lower relative to other features, with exception to the intangible cost of human life. For example, a rockfall fatality may involve a single rock that strikes a vehicle. While there is a significant individual consequence, the roadway may not be damaged and the economic effects to the corridor are not prolonged.

To address this situation in the example corridor, the risk for loss of life from the critical rockfall features identified in the first tier assessment could be evaluated using the individual risk method presented in AGS (2000). This risk can be calculated as follows:

$$R_{(\text{annual probability of fatality})} = P_{(H)} \text{ x } P_{(S:H)} \text{ x } V_{(\text{Individual})} \text{ x } P_{(T:S)}$$

Where:
$P_{(H)}$: Probability of the event occurring (0 to 1.0)
$P_{(S:H)}$: Conditional probability of spatial impact by the hazard (probability of rockfall at a given location striking a present vehicle)
$V_{(\text{Individual})}$: Vulnerability (probability) of life loss due to impact of event
$P_{(T:S)}$: Temporal probability of spatial impact by hazard (i.e., the probability of a vehicle occupant in the area of impact)

The purpose of this risk analysis would be to provide a range in annual probability of fatality for each geotechnical feature in the corridor. Depending on the goals of the agency, the fatality risk could be evaluated against performance measures for safety in a transportation asset management plan.

PROJECT PLANNING AND INCORPORATION WITH TRANSPORTATION ASSET MANAGEMENT

The data from the second tier assessment can be used to support the agency transportation asset management goals, such as safety, mobility and preservation. The data presented in Table 5 would be the basis for identifying the projects or features with the highest potential risk to corridor performance. As part of project prioritization and planning for the corridor life cycle, the decision process should consider expected annual cost in the year improvement is performed as well as subsequent years and relative to the degree of risk reduction. While a site may have a high risk, that should not be the only criteria for selection. The purpose of risk assessment and life cycle cost analysis is to optimize the expenditure of available funds while maximizing asset class risk reductions for the entire system. Trade-off analysis is required to make project selections based on the need to achieve the greatest systematic risk reduction at the corridor or agency level. As the asset management practice evolves, an agency should be able to recognize improving performance metrics related to safety, maintenance, and mobility.

In many situations, the funds for a separate mitigation project may not be available; however, a separate improvement project may be planned in the corridor (e.g. bridge replacement or pavement rehabilitation). In these situations, there may be excess budget or savings that could be directed to other efforts under the same project mobilization. Using a geotechnical asset management plan with the above assessment methods, the extra funds could be allocated in a manner that achieves the greatest reduction in risk and improves any performance measures that are below the agency criteria. This would be accomplished by modeling different combinations of project funding strategies for the critical features along the corridor.

For many geotechnical asset types, regular maintenance expenditures are required. As mentioned previously, the selection of improvements should consider lifecycle costs. Additionally, the level of staff maintenance commitment must be established in consensus with Agency Management. For a rockfall site, the maintenance needs can include such things as removal of debris behind barriers and fences, cleaning of shoulder ditches, patching of steel mesh on a steep slope, and repair of proprietary metal fence systems. Groundwater drains can require periodic flushing and repair of outlets. These are just some examples of the maintenance activities that are attributable to geotechnical features. If maintenance cannot be completed either by agency staff or contractors, the service life of assets will be greatly reduced, as well as the level of risk reduction. When assets are not maintained, conditions can deteriorate causing emergency situations and diversion of agency funds.

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CHAPTER 6 — RECOMMENDATIONS

The methods and procedures to perform geotechnical asset management are available and have been demonstrated for other infrastructure types or in international practices. The purpose of this document is to provide an overview of the concept of geotechnical asset management and needed developments to move the practice forward. Initiation of a program is the most important step and the geotechnical asset management and risk based concepts presented herein are an initial attempt to develop an approach that can be implemented to meet the goals of transportation asset management.

Based on the literature reviewed for this paper and discussions with FLH personnel, the following steps are recommended to effectively implement geotechnical asset management for FLMAs, as well as other state and federal roadways.

DEFINE PERFORMANCE GOALS AND MEASURES

To manage any asset there must be goals and performance measures to track the success of the plan. Performance measures provide a quantitative basis for planning and selecting of projects. Ideally, goals should be established by agency leadership to satisfy the intent of transportation asset management. In situations where agency performance goals do not exist, geotechnical asset management is still recommended because of the demonstrated value. In these situations, the geotechnical performance goals can be developed by the geotechnical discipline leadership within the agency.

EFFICIENT ASSESSMENT PROCESSES

Because of the constrained funding environment in most transportation agencies, a rapid and efficient means of inventory and assessment is likely required for acceptance of the geotechnical asset management process. Most federal and state agencies are not able to increase staff resources at this time. Therefore, a geotechnical asset management program must be designed to be performed without a large increase in staff or consultant expenses. As demonstrated by the NPS WIP, there is a significant cost associated with a comprehensive inventory program for retaining walls and additional effort is still required to implement the WIP results into a geotechnical asset management plan. As described herein, there are several examples of rapid, multi-tier assessment techniques that can be used to concentrate agency resources on the critical geotechnical features.

For geotechnical asset management to be successful, it is important to transition from evaluating hazards to assessing the risk from the hazard. By directing limited resources towards the inventory and assessment of hazards, an agency may be misdirecting effort to features that are not critical to the performance goals.

USE INNOVATIONS IN DATA MANAGEMENT AND COLLECTION

There are numerous technical improvements related to the electronic data collection and geo-referencing of field observations as well as data access, storage, and visualization. Many of these tools are currently being implemented within the FLH. Based on discussions with FLH staff, the ongoing access and standardization of data formats will be valuable improvements to a geotechnical asset management approach.

The evaluation of geotechnical features is often based on observational methods. There are examples from other agencies that could supplement collection of performance data for FLMAs. These include maintenance activity registers that are GIS based and automatically transmit data to the agency data management system and the use of phone and internet tools for the traveling public to report events they may observe. By collecting and storing this information, the probability estimates used in the risk assessment will be more reliable, which will improve the asset management process.

CORRIDOR APPROACH TO ASSET MANAGEMENT

Within a corridor there will be several geotechnical features that influence the mobility, safety, and preservation goals. The geotechnical features that could be included in a geotechnical asset class will vary on the basis of geologic and geographic conditions. The selection of features also may depend on the performance measures of the agency, which can vary. For example, the performance goals for a roadway that provides the primary access into a national park may differ from the performance goals for a forest highway. Therefore, the asset management plans should be specific to the needs of each roadway.

Additionally, the asset management of several geotechnical features as a single class within the context of a corridor is required for development of accurate conclusions. Omission of a feature type or separation of asset management plans may not satisfy the performance goals. For example, the geotechnical failures summarized in the section *"Examples of the Value of Geotechnical Assets"* (page 6), occurred on roadways that also have pavement and bridge management systems, yet it was the geotechnical feature that caused the significant interruption to corridor performance. A similar example can be expected in the situation where retaining wall or tunnel features are managed, but an unmanaged landslide creates the immediate and highest risk to the corridor. When incorporating risk, geotechnical asset management will only be successful when all features that create risk are included in the assessment.

The two-tier risk assessment approach will quickly identify corridor locations with the greatest risk to performance measures. These data will serve as the basis for well-defined project selection decisions; however, the funding for project specific improvements may not be available. Regardless, these locations should be identified in the data management systems for incorporation into the planning process. Identification as a high risk feature should not be the only criteria for mitigation; rather, additional analysis should be performed to determine the optimum strategy for obtaining the greatest degree of risk reduction for multiple features in a corridor or agency. Assuming the principles of asset management are used, the critical geotechnical asset needs can be compared with other assets to develop projects that satisfy the agency goals in the most cost-effective manner.

COMMIT TO THE PROCESS

The lessons learned from published case histories consistently indicate a need to commit to the asset management process. Per AASHTO (2011a), transportation asset management is a process that improves with time. This improvement results from the collection of data and comparison with performance metrics. There are several literature examples that support the value of geotechnical asset management. As summarized by Perry and others, *cuttings* (2003) and Perry and others, *embankments* (2003), studies on the benefit of a proactive maintenance and renewal strategies (i.e., geotechnical asset management) for embankments indicate life-cycle cost savings of approximately 60 to 80 percent. Based on this conclusion, ***there is an agency cost associated with inaction on geotechnical asset management***.

The established rockfall hazard programs within several agencies and the few recent retaining wall and unstable slope programs are examples of a form of asset management. In their current format, it appears unlikely there will be widespread expansion of these programs within public transportation agencies. This is because of the need for large staff mobilizations or consultant support at a time when transportation budgets are limited. Furthermore, these programs can create a ranking and inventory of needs, but are not designed to qualitatively support transportation asset management.

The example geotechnical asset management program presented in Chapter 5 is based on established practices in other countries or infrastructure types. Furthermore, the program processes should not require a significant mobilization of personnel or equipment. The risk based outcomes of the proposed geotechnical asset management plan can easily be adapted to the typical performance measures of a transportation asset management plan. A demonstration project on a FLMA corridor is recommended to refine processes presented herein and illustrate the efficiencies and value added to life-cycle.

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APPENDIX A — EXAMPLE DECISION TREES FOR QUANTITATIVE EVALUATION OF GEOTECHNICAL RISKS

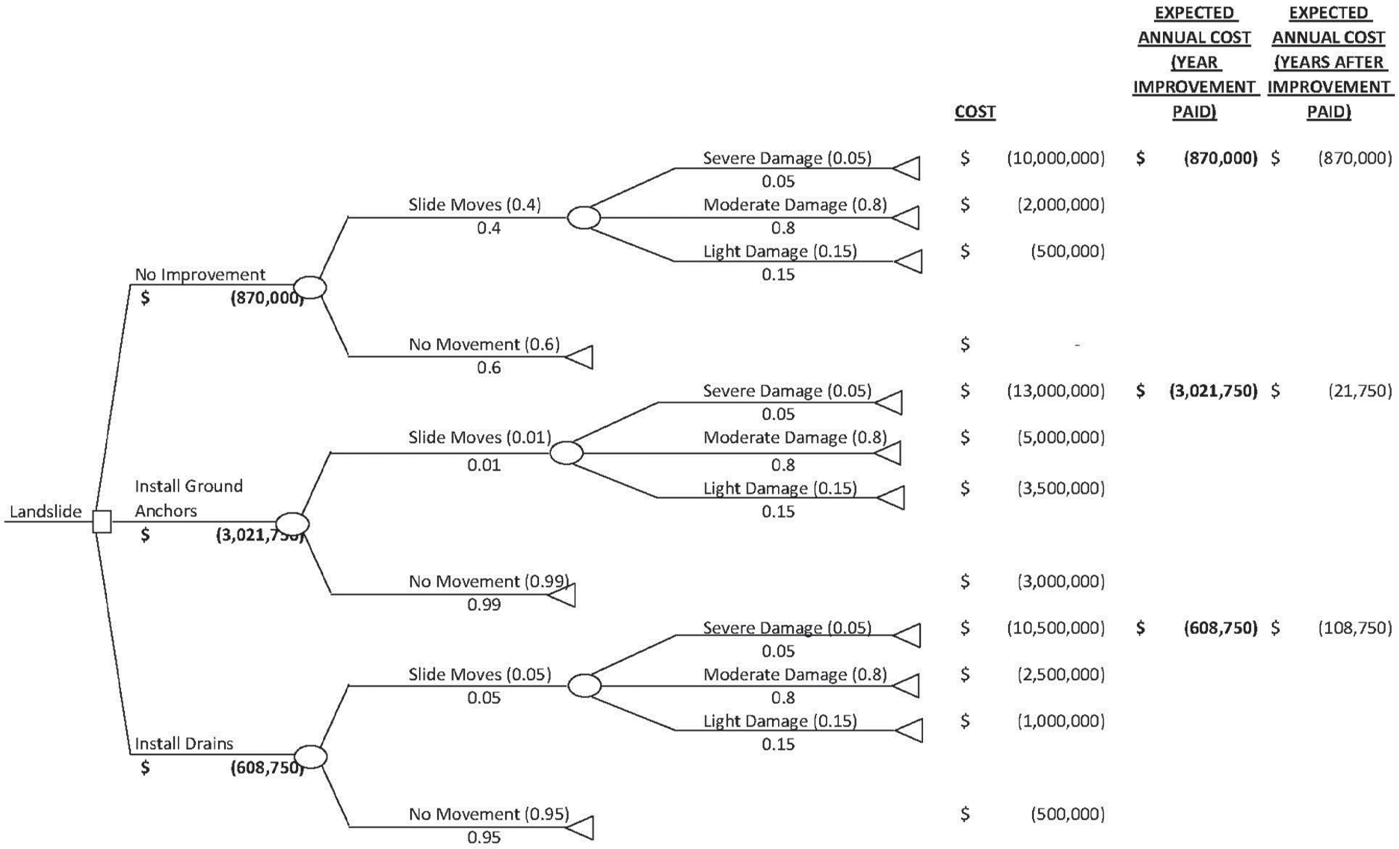

Figure 16. Chart. Example decision tree for a landslide.

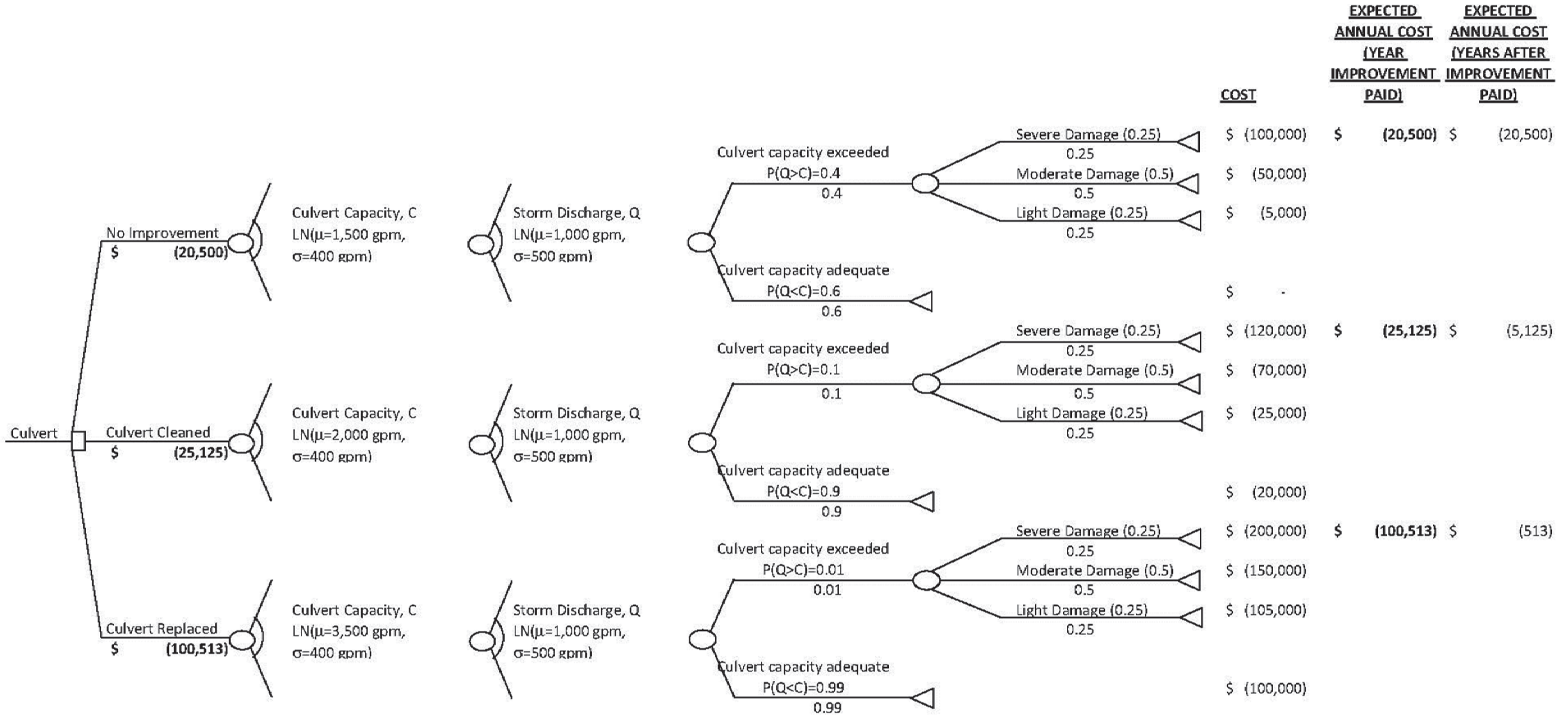

Figure 17. Chart. Example decision tree for a culvert crossing.

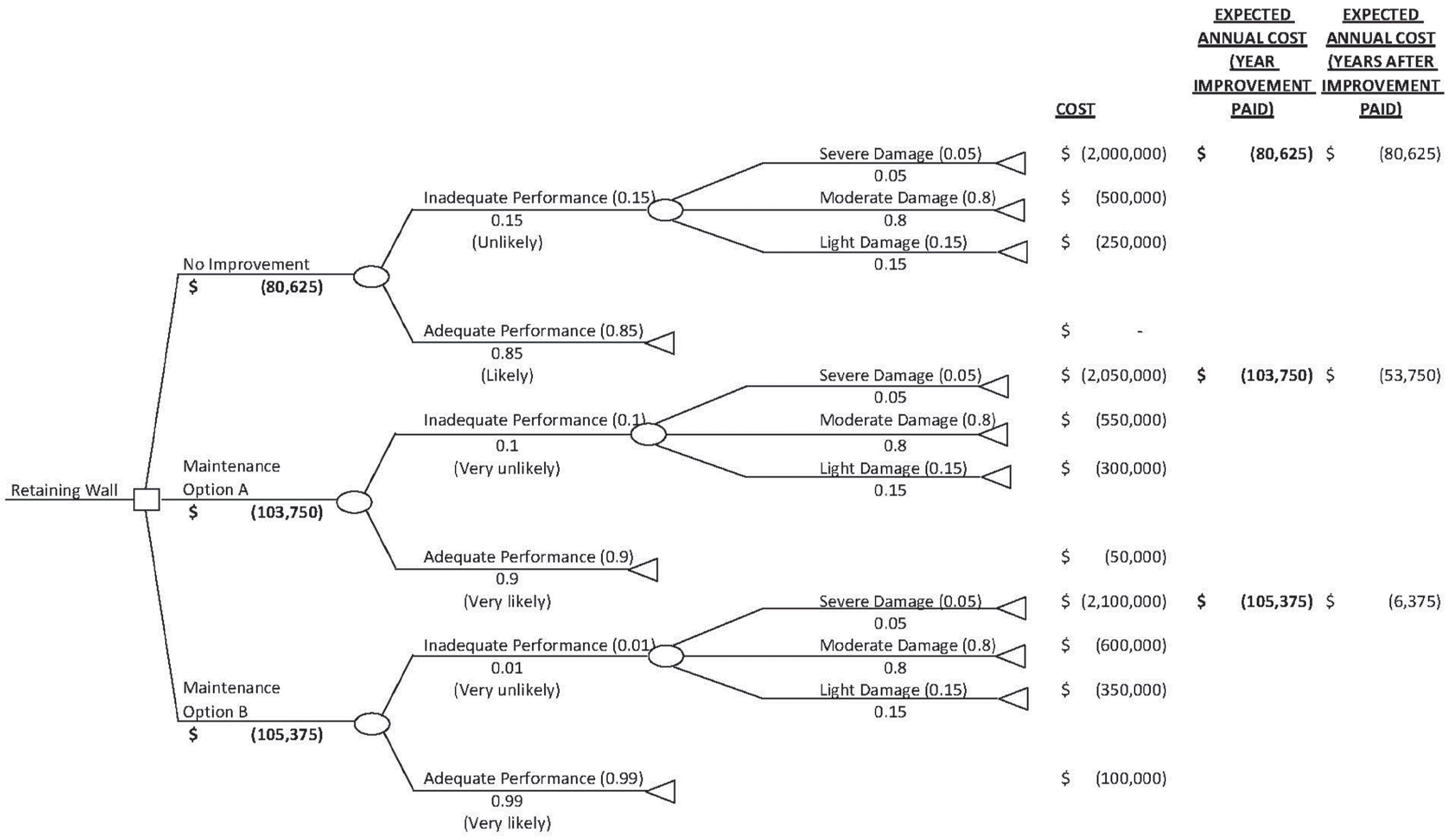

Figure 18. Chart. Example decision tree for a retaining wall.

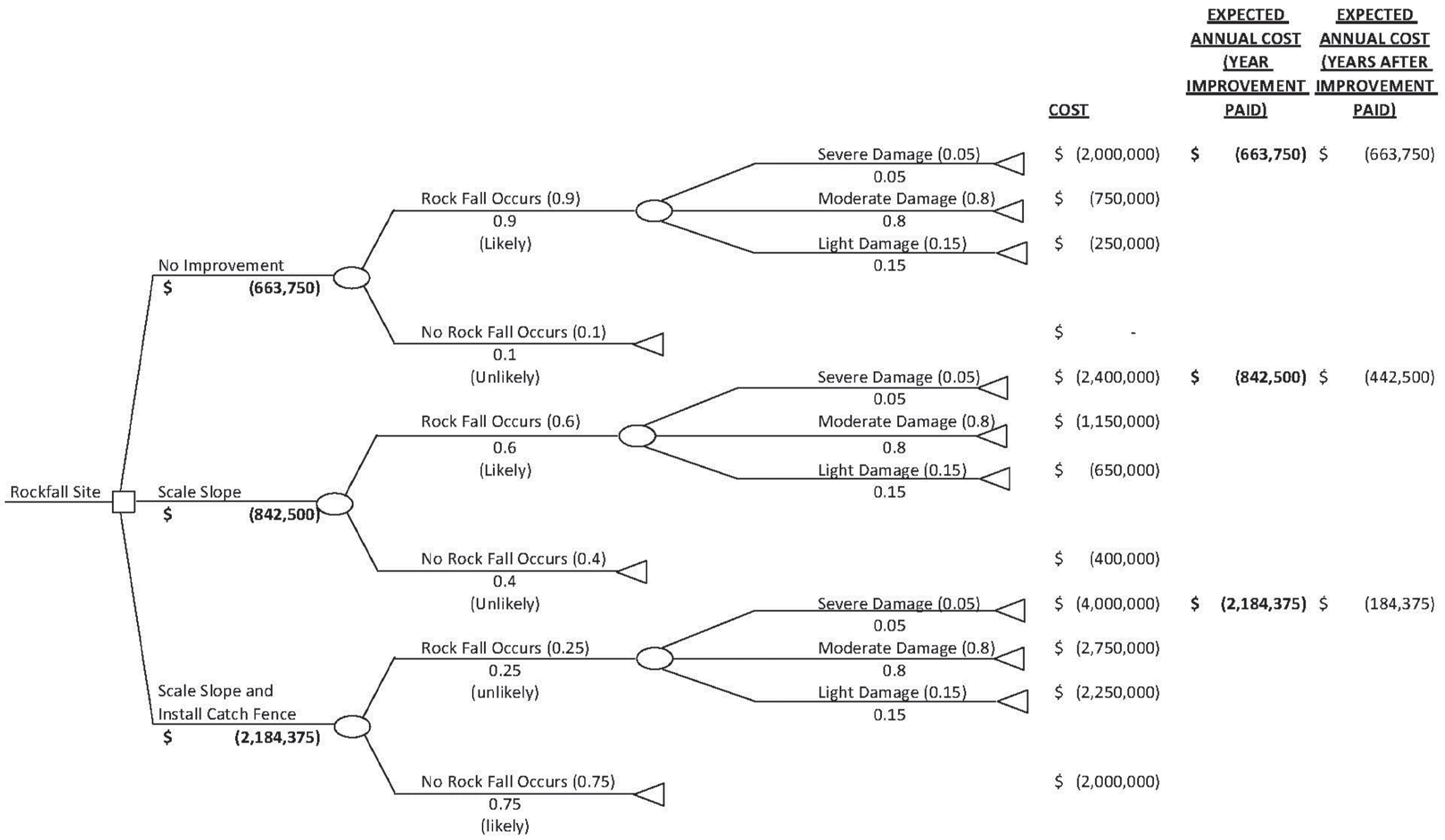

Figure 19. Chart. Example decision tree for a rockfall site.